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Potential Health and Environmental Impacts Attributable to the Nuclear and Coal Fuel Cycles

ORIGINAL

Final Report

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

R. L. Gotchy

CDL

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Potential Health and Environmental Impacts Attributable to the Nuclear and Coal Fuel Cycles

Final Report

Date Published: June 1987

R. L. Gotchy

Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

ABSTRACT

Estimates of mortality and morbidity are presented based on present-day knowledge of health effects resulting from current component designs and operations of the nuclear and coal fuel cycles, and anticipated emission rates and occupational exposure for the various fuel cycle facilities expected to go into operation during the next decade. The author concluded that, although there are large uncertainties in the estimates of potential health effects, the coal fuel cycle alternative has a greater health impact on man than the uranium fuel cycle. However, the increased risk of health effects for either fuel cycle represents a very small incremental risk to the average individual in the public for the balance of this century. The potential for large impacts exists in both fuel cycles, but the potential impacts associated with a runaway Greenhouse Effect from combustion of fossil fuels, such as coal, cannot yet be reasonably quantified. Some of the potential environmental impacts of the coal fuel cycle cannot currently be realistically estimated, but those that can appear greater than those from the nuclear fuel cycle.

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PREFACE

This report deals with a subject that is difficult because of its complexity, the diversity of risks and risk parameters, and, especially, the gaps and limitations of the underlying data.

The work was originally undertaken to assist in comparisons of alternative energy sources in connection with environmental impact statements, mandated by the National Environmental Policy Act, in support of evaluation of license applications for nuclear power plants. Inclusion of a comparative risk criterion (relative to alternative viable electric power sources) in the Commission's proposed safety-goal policy statement has created a possible additional point of pertinence of the report's subject to NRC actions and policies.

The predecessor of this report was issued for comment in September 1977, with a commitment to update the draft to consider comments received and the results of a wide-ranging study by the Committee on Nuclear and Alternative Energy Systems (CONAES) of the National Research Council, National Academy of Sciences. The CONAES report was released to the public in January 1980. However, the Council, late in 1982, decided not to complete and publish the report of the CONAES Risk and Impact Panel, which was to detail the findings and document the detailed analyses of comparative risk. That decision was apparently taken on a Council judgment that the softness of underlying data would be an impediment to producing a comparison that merits confidence.

Thus, while this report represents a state-of-the-art effort, the author cannot claim that his treatment of the subject is comprehensive or definitive. He hopes, however, that the report may help to inform and enhance public debate (as provided for by Section 141(b) of the Atomic Energy Act, as amended), and it is to that end that the Nuclear Regulatory Commission's (NRC's) Office of Nuclear Reactor Regulation has authorized issuance of this report.

The report is a compilation of results and views from many sources. Interpretations and unattributed views are the author's own. The report has been neither approved nor disapproved by the NRC.

Readers are advised to keep in mind that (1) the principal modifications to the 1977 draft of this report were completed in 1981, and are largely based on information available through 1980; (2) the analyses of the potential environmental and public health effects of the nuclear fuel cycle are based on expertise that is both internal and external to the NRC and reflect substantial work by the staff and others, including contract researchers; (3) comparable analyses of the potential effects of the coal fuel cycle, however, are based primarily on the work of experts outside the NRC and include knowledge gained from the literature, in discussions with recognized authorities, conferences, and workshops; and (4) since estimates of risk are based on evolving knowledge, technology, and regulatory practices, it is expected that many of the estimates presented in the report will also be subject to change.

The Commission has a continuing interest in the risks from coal and nuclear energy sources and the relation among such risks. Any further comments on the subject continue to be welcome. They should be addressed to Mr. Frank J. Congel, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555.

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POTENTIAL HEALTH AND ENVIRONMENTAL IMPACTS ATTRIBUTABLE TO THE NUCLEAR AND COAL FUEL CYCLES

1 INTRODUCTION

The National Environmental Policy Act of 1969 (NEPA) requires the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to ensure, among other things, that the Nation may

> Fulfill the responsibilities of each generation as trustee of the environment for succeeding generations.
>
> Assure for all Americans safe, healthful, and productive and pleasing surroundings.
>
> Attain the widest range of beneficial uses of the environment without degradation, risk to health and safety, or other undesirable and unintended consequences.[1]

Furthermore, with respect to major Federal actions significantly affecting the quality of the human environment, Section 102(2)(c) of NEPA calls for consideration of, among other things,

> The environmental impact of the proposed action.
>
> Alternatives to the proposed action.[1]

It is clear that the major alternative to nuclear power for meeting the Nation's baseload electrical needs for the rest of this century is coal power, although other alternatives (including conservation) will be contributing needed power.

The Nuclear Regulatory Commission's (NRC's) environmental statements have discussed the impacts of the coal fuel cycle in terms of economics, and generically address these impacts in terms of land and water use. However, on January 25, 1977, an Atomic Safety and Licensing Appeal Board rendered a decision that stated:

> A disproportionately large part of the analyses comparing the coal and nuclear fuel cycles is focused on costs rather than environmental considerations.
>
> While the effects on human and animal life of the emissions from the proposed nuclear plant are discussed in detail, there is no corresponding discussion with respect to the postulated coal plant.
>
> No mention is made of the environmental effects of the coal fuel cycle.

> Although exact identity in treatment with respect to every aspect of environmental comparison of alternatives may not be required, this kind of comparison goes to the heart of NRC's duty under NEPA, where coal and nuclear power are shown to be the only two feasible alternatives.[2]

As a result of the above decision, the NRC staff prepared testimony for ongoing hearings, and similar input for current environmental statements where such considerations were lacking. That testimony, which was presented in numerous public hearings, was the basis for a draft report (NUREG-0332)[3] issued in September 1977 for public comment.

After receiving comments from Federal and State agencies, industry, and concerned members of the public, and reviewing a report by the National Research Council, National Academy of Sciences Committee on Nuclear and Alternative Energy Systems,[4] the author prepared this final report, and incorporated as many of the comments and as much new data as were appropriate.

In the analyses that follow, an average measure of the risk is estimated by multiplying the probabilities that an event will occur by the consequences of that event. The resultant risk is then expressed as a number of consequences expected.

In the present state of knowledge, all health risk assessments of energy systems contain fairly large uncertainties. Some sections of the assessments, such as those dealing with risk of accidental death among coal and uranium miners, can be estimated reasonably satisfactorily on the basis of recent experience. Other parts, such as those dealing with the potential risk associated with serious accidents in nuclear power plants, can only be estimated to within perhaps one or two orders of magnitude because of the absence of actual experience. Nevertheless, it is in the vital interest of the Nation that such assessments be made and updated as new information becomes available. Although many of the numerical values of health effects presented later in this document, in text and in tables, will be given to more than one significant figure, it should be recognized that this is not an indication that these effects are known with even that degree of precision.

In the following discussions, all health risk and environmental impact estimates are normalized to the annual operation of a modern, coal-fired or light-water-cooled nuclear power plant that generates 1,000 megawatt-yr (MW-yr) of electric power (that is, a GW(e)-yr). Thus, the reader can extrapolate the estimates to any number of power plants over any period of time simply by multiplying by the total projected electric power for these plants.* A similar unit is defined for light-water reactors (LWRs) in Title 10 of the Code of Federal Regulations (10 CFR), Part 51,[5] as a reference reactor year (RRY) and represents the estimated releases of radioactivity from generating 0.8 GW(e)-yr of electric power (a 1,000-MW(e) plant operating at 80% of capacity for 1 year).

---

*For example, one hundred 1,000-MW(e) plants operating at 65% capacity for 30 years each would generate about 2,000 GW(e)-yr of electric power. Thus, the impact would be about 2,000 times the impact presented in this report per GW(e)-yr.

2

2 POTENTIAL HEALTH AND ENVIRONMENTAL IMPACTS OF THE NUCLEAR FUEL CYCLE

In the discussions that follow, the potential impacts of the nuclear fuel cycle range from potential health impacts of normal radiological releases on the public, risks to radiation workers, risks of accidents to the public and fuel cycle workers, and more diffuse risks such as those from diversion of nuclear materials for use by terrorists and the potential global risks associated with proliferation of nuclear weapons. Where possible, the risks are quantified in terms of the operation of a 1,000-MW(e) nuclear power plant for a period of 1 year, plus the risks from operation of the supporting fuel cycle. Finally, those risks that can be quantified are compared with other better known risks, providing the reader with a different perspective to the potential risks of the nuclear fuel cycle.

A diagram of the three current options for the light-water-cooled reactor fuel cycle is shown in Figure 1 to assist the reader in understanding the discussions that follow.

2.1 Potential Radiological Health Impacts of the Nuclear Fuel Cycle

2.1.1 Radiological Effluents

The radiological effluents estimated for the supporting fuel cycle (that is, everything except the power reactor itself) for one RRY are specified in 10 CFR Part 51, Table S-3. These effluents represent the sum of the maximum probable releases occurring from reprocessing, waste management, and transportation of wastes for either of two options: no recycle of uranium or plutonium (the so-called throwaway option), or recycle of uranium only. The third option, shown in Figure 1, recycle of uranium and plutonium, results in population doses that are somewhat less but not significantly different from those for recycle of uranium only.

These effluents (gaseous and liquid) were selected from detailed studies, such as NUREG-0002, "Final Generic Environmental Impact Statement on the Use of Mixed Oxide Fuel in Light-Water-Cooled Reactors - Health, Safety and Environment" (GESMO),[6] a and the extensive Table S-3 Rule Hearings, conducted over several years by NRC, which resulted in the current rule. The radiological effluents used for this health risk assessment are shown in Table 1. Detailed bases are provided in NUREG-0002; "Environmental Survey of the Uranium Fuel Cycle," WASH-1248;[7] "Environmental Survey of the Reprocessing and Waste Management Portion of the LWR Fuel Cycle," NUREG-0116 (Supplement 1 to WASH-1248);[8] "Public Comments on the Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," NUREG-0216 (Supplement 2 to WASH-1248);[9] and "Record of the Final Rulemaking Pertaining to Uranium Fuel Cycle Impacts From Spent Fuel Reprocessing and Radioactive Waste Management," Docket No. RM-50-3.[10]

Because the GESMO study represented only a 26-year period (1975 to 2000) and the environmental dose commitment period was limited to 40 years for each year of the 26-year period, it was necessary to extend the time integral for radon-222

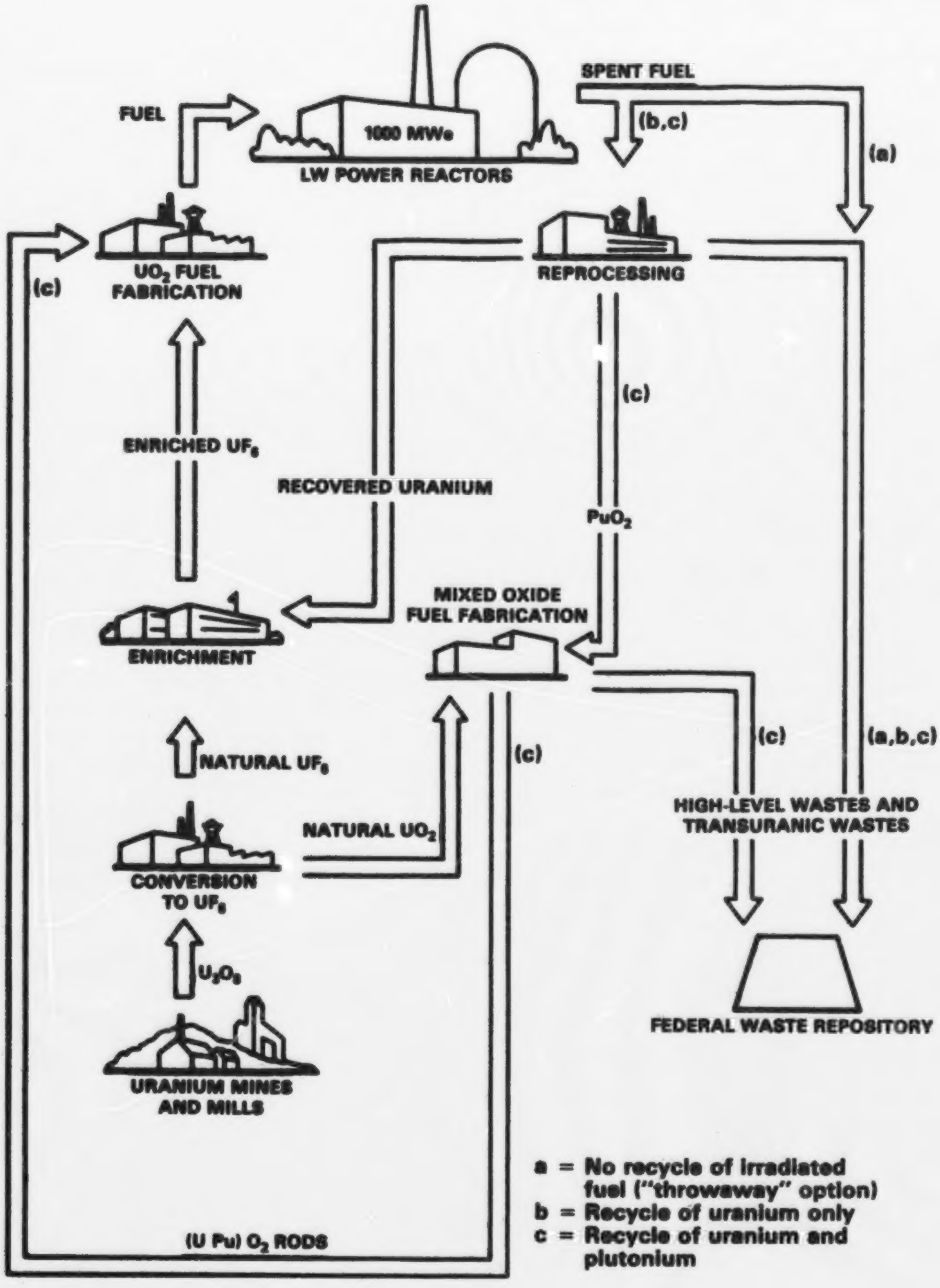
FUEL
1000 MWe
LW POWER REACTORS
SPENT FUEL
(b,c)
(a)
UO_2 FUEL FABRICATION
(c)
REPROCESSING
(c)
ENRICHED UF_6
RECOVERED URANIUM
PuO_2
MIXED OXIDE FUEL FABRICATION
ENRICHMENT
NATURAL UF_6
(c)
(c)
(a,b,c)
HIGH-LEVEL WASTES AND TRANSURANIC WASTES
NATURAL UO_2
CONVERSION TO UF_6
U_3O_8
FEDERAL WASTE REPOSITORY
URANIUM MINES AND MILLS
(U Pu) O_2 RODS
a = No recycle of irradiated fuel ("throwaway" option)
b = Recycle of uranium only
c = Recycle of uranium and plutonium

Figure 1 Current options for the nuclear fuel cycle

Table 1 Radioactive effluents from the nuclear fuel cycle per reference reactor year (0.8 GW(e)-yr)*

Source of the release	Radionuclide released	Curies released
	Gaseous	
Uranium mines	Rn-222	5,300-19,000**
Uranium mills and mill tailings (Note: Essentially all of the radiological impact is from Rn-222)	Ra-226	0.020
	Th-230	0.020
	U-234	0.0044
	U-235	0.000030
	U-238	0.030
	Rn-222	1,500-12,000**
UF_6 conversion plants	U	0.0015
Uranium enrichment plants	U	0.002
	Tc-99***	0.046
Fuel fabrication plants	U	0.0002
Light-water-cooled nuclear power plants (Note: Over 90% of the total radiological impact is from H-3, C-14, Kr-85, and Xe-133)	H-3	1,200
	C-14	8.0
	Co-58	0.015
	Co-60	0.06
	Kr-85	470
	Sr-90	0.0010
	Xe-133m	120
	Xe-133	12,000
	Xe-135	1,100
	I-131	0.33
	Cs-134	0.005
	Cs-137	0.010
Fuel reprocessing plant (Note: Over 90% of the radiological impact is from H-3, C-14, and Kr-85)	H-3	18,100
	C-14	24
	Kr-85	400,000
	Sr-90	0.016
	Tc-99***	0.11
	Ru-106	0.14
	I-131	0.83
	Cs-134	0.109
	Cs-137	0.055
	U-234	0.000015
	U-235	0.000004
	U-238	0.000020
	Pu-238, Pu-239	0.00088
	Pu-241	0.020
	Am-241	0.000014
	Am-243	0.0000011
	Cm-242	0.0015
	Cm-244	0.00011
Geologic repository	I-129	1.3

See footnotes at end of table.

Table 1 (Continued)

Source of the release	Radionuclide released	Curies released
	Liquid	
Uranium mill tailings	U and daughters	2.0 (released to ground)
UF_6 conversion plant	Ra-226	0.0034
	Th-230	0.0015
	U and daughters	0.044
Uranium enrichment plant	U and daughters	0.02
Fuel fabrication plants	Th-234	0.010
	U and daughters	0.02
Light-water-cooled nuclear power plants (Note: Most of the radiological impact is from Cs-134 and Cs-137)	H-3	240
	Mn-54	0.0015
	Co-60	0.0089
	I-131	0.28
	Cs-134	0.02
	Cs-137	0.034
Shallow land burial	Tc-99***	1.2

*Only the major releases, in terms of quantity and potential radiological impact, are included. Multiply all releases by 1.25 to convert to GW(e)-yr releases.

**100- to 1,000-year period; includes long-term emanation from tailings piles (see Ref. 11 for further details).

***No Tc-99 source terms are specified in Table S-3 (10 CFR 51) at this time. The values for Tc-99 shown here are based on current but conservative NRC staff estimates, and are subject to future revisions (see Ref. 12 for further details).

(Rn-222) emissions from uranium mines and mill tailings piles to cover the maximum period which the inherent uncertainties in such projections reasonably permit. A detailed discussion of these uncertainties follows in Section 2.1.2. However, the Rn-222 issue has been thoroughly studied and soundly debated in numerous reactor licensing hearings (see, for example, Ref. 13), and in recent hearings[14] followed by generic decisions by an NRC appeals board which support the general approach used in this assessment.[15,16] The Rn-222 source terms selected for this assessment represent a reasonable range of releases that might occur over periods of from 100 to 1,000 years into the future. These estimates are based on a recent reevaluation of this question by the NRC, and the reader is referred to Reference 11 for details on the methods used for estimating Rn-222 releases.

It should be stressed that, for the time periods examined (that is, up to 1,000 years into the future), actual releases are expected to be lower than those shown in Table 1. This statement is particularly true for tritium (H-3), krypton-85 (Kr-85), carbon-14 (C-14), and particulates because engineering and technological improvements appear likely to greatly reduce these releases. (See, for example, Ref. 6, pp. IV E-23 through IV E-28.)

2.1.2 Environmental Transport Models

To estimate the radiation doses to populations, it is necessary to use environmental transport models that describe the dispersion, deposition, and resuspension of hundreds of radionuclides released by the fuel cycle during normal and accident conditions. The models used for normal operations are described in detail in NUREG-0002 (GESMO)[6*] and the Table S-3 hearing transcripts and reports.[8-10] The environmental transport model for gaseous releases (normally and abnormally occurring) is a so-called wedge model that limits vertical dispersion to a maximum height of 1,000 m (3,280 ft), which is typical for nonbuoyant near-surface releases. After several miles of transport from the point of release, a fairly uniform cross-sectional concentration for the balance of the "first pass" across the United States results.

Once the plume leaves the United States, the volatile radionuclides of sufficiently long radiological half-life are assumed to mix uniformly in the world's atmosphere or hydrosphere. Thus, longer-lived nuclides such as tritium (12 years), C-14 (5,700 years), and Kr-85 (10 years) have at least two exposure modes to consider: first-pass exposure and subsequent exposures. Global dispersion of Kr-85 is simple to model because it is known to mix fairly uniformly in the world's atmosphere (3.8×10^{21} liters [1.3×10^{20} ft^3]) over a period of time that is short relative to its half-life. However, H-3 and C-I4 are more difficult to model. After the first pass, tritium was reasonably assumed to mix in the earth's circulating water volume (2.7×10^{19} liters [7.1×10^{18} gal]), and C-14 was assumed to mix initially in the world's atmosphere where it is gradually removed to the ocean over a period of time that is short relative to its half-life. Details of the C-14 long-term dispersion model used in this assessment are available in a recent Oak Ridge National Laboratory report.[17] No environmental removal mechanisms (such as losses to deep ocean water), only radioactive decay, were conservatively assumed for H-3 and Kr-85.

After the first pass, it was necessary to devise a method for determining long-term dose commitments for iodine-129 (I-129) and technetium-99 (Tc-99) because of their very long half-lives (17 million years and 210,000 years, respectively). It was assumed that I-129 would distribute uniformly in the world's stable iodine pool (6×10^{16} g [1.3×10^{14} lb]). It was conservatively assumed that no other physical removal mechanisms were operating. (Radioactive decay in 1,000 years is insignificant.) Details on the model are presented in Reference 9.

Technetium-99, the first man-made element, is more difficult to model because there is no stable technetium pool in the world in which to determine a final specific activity as was done for I-129. To upper bound the potential dose impacts, it was assumed that after the first pass across the United States, the Tc-99 released would distribute uniformly in the world's circulating water volume (same assumption as for H-3). It was conservatively assumed that no physical removal mechanisms (for example, precipitation or other means of deposition in sediments, or radioactive decay) were operating.

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*See, in particular, Section IV J.

In the special case of Rn-222 emissions from uranium mining and milling, the models used were developed for NRC by Argonne National Laboratory[18] (populations within 80 km [50 miles] from a model facility) and the National Oceanic and Atmospheric Administration[19] (populations more than 80 km from a model facility). These models are more sophisticated than those used for GESMO, and result in more realistic evaluations of population doses. In general, these dose estimates are of the same order of magnitude as those in GESMO. More details are provided in References 11, 18, and 19, Appendix VI.

For gaseous radioactive releases from light-water-cooled reactor accidents, the atmospheric dispersion as described by the Reactor Safety Study[20] was assumed. These dispersion estimates are based on a modified Gaussian dispersion model (with vertical dispersion limited by the seasonal mixing depths). Stability, precipitation, wind speeds, and directions are based on actual meteorology measured at several different types of U.S. nuclear power station sites (valley, river, lake, ocean, and plains) over extended periods. For details on the models, see Reference 20, Appendix VI.

2.1.3 Radiation Dose Models

The radiation dose models used in this assessment are those that permit estimation of collective population dose commitments.* These doses are collective in that they represent the summation of all the individual doses in an exposed population. These doses are also a commitment because they represent the total collective dose over extended periods from all radionuclides released per GW(e)-yr. Two types of commitments are considered in this assessment. For each individual in the exposed population, a 50-year dose commitment is first calculated for each radionuclide that is taken into the body through inhalation and food pathways during the year a modern nuclear power plant and its supporting fuel cycle operate, as well as external exposures from airborne radioactivity and radioactivity deposited on the ground (and resuspended) during that year. The second type of dose commitment results from similar exposures to these same radioactive releases during subsequent years. The summation of the 50-year dose commitments for each of these years is called the environmental dose commitment (EDC). In practice, the EDC estimates are usually limited to periods for which reasonable estimates of population doses can be made. In this assessment, a 100- to 1,000-year EDC has been used to estimate the potential health effects that the production of 1 GW(e)-yr might cause among people now living and those living in the distant future.

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*For example, the annual radiation dose to the total body of an average American is about 0.1 rem (1.0 millisievert) from natural background radiation. Most of the dose occurs during the year from external radiation (cosmic rays and terrestrial gamma radiation) and from potassium-40 in the food we eat. However, some internally deposited primordial radionuclides (uranium, thorium, and actinium series) continue to give doses to certain specific organs (for example, lung and bone) for many subsequent years (a committed dose). The collective annual total body dose commitment from natural background radiation in the United States is about 0.1 rem/yr x 220 million persons, or 22 million person-rem (0.22 million person-sieverts).

The EDCs consider, within the limits of the present state of knowledge, collective radiation doses from external exposure to radioactivity suspended in air and water, deposited on the ground and in sediments, and taken up through all potential food pathways (milk, drinking water, red meat, fish, invertebrates, vegetables, and grains) following initial deposition and redistribution in the environment. In general, dose commitments are determined by the concentrations of the radionuclides in air and water. For the U.S. population, most of each 50-year dose commitment is determined by the "first pass" of those radionuclides over the United States. Only for a few very long-lived radionuclides, such as C-14 and I-129, can the subsequent passes contribute significantly to the total EDC. The special case for Rn-222 emissions from uranium mines and mills will be discussed below in detail because the potential impacts could dominate the impacts of the fuel cycle. Details of the models are presented in References 6-9, but because of space limitations are not discussed further in this report.

In the case of Rn-222 releases, even though Rn-222 is a short-lived radionuclide (3.8-day half-life), its predecessors have much longer half-lives. As a result, although Rn-222 impacts are primarily restricted to the U.S. population from the first pass of the Rn-222, these impacts may continue to accumulate over long timespans depending on factors that may increase or decrease Rn-222 emissions with time. In the GESMO Hearing, the Rn-222 impacts were incorrectly estimated because of a factor-of-10 error in the total body dose factor for lead-210 (Pb-210) in International Commission on Radiological Protection (ICRP) Publication 2.[21] The estimates were subsequently corrected by the NRC staff in a memorandum to the GESMO Hearing Board.[22] As a result, the GESMO population doses/commitments (Table IV J(E)-1) for uranium mining and milling were reduced by factors of 7.7 for uranium mining and 6.1 for uranium milling (no recycle), and similar factors for the other recycle options.

In addition, the staff subsequently concluded that the ICRP-2 lung model was inappropriate for Rn-222 and its short-lived progeny because it calculates an averaged dose for the entire lung while the critical tissue is the bronchial epithelium. This assessment, therefore, used the recommended dose conversion factors from Reference 11 for Rn-222 and daughters, based on more appropriate models for dose to the bronchial epithelium, as well as total body and bone.

For I-129 and Tc-99, long-term U.S. population dose estimates are believed to be conservative because of the assumptions made for environmental transport in the preceding section. The specific activity model for I-129 results in 1.7×10^{-5} picocuries of I-129 per gram of stable iodine per curie of I-129 released to the biosphere. The average dose rate to the thyroid gland would be about 7.1×10^{-9} millirem (mrem) per year per curie of I-129 released. In the case of Tc-99, the long-term dose would come from ingestion of seafood, which uptakes Tc-99 from lower trophic levels, resulting in bioaccumulation in edible flesh. Bioaccumulation and dose factors for salt water species are discussed in more detail in USNRC Regulatory Guide 1.109 (Rev. 1, October 1977).[23] The current NRC model for Tc-99 indicates that for periods of about 1,000 years after the initial release, the average individual radiation dose commitment per curie of Tc-99 released to gaseous and liquid pathways would be about 9×10^{-8} mrem per year and 3×10^{-9} mrem per year (total body risk equivalent dose), respectively.[12] Most of the accumulated doses accrue in the gastrointestinal tract and kidney. Essentially, the entire radiation dose to U.S.

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populations from I-I29 and Tc-99 up to 1,000 years into the future results from the first pass of these nuclides in the United States.

2.1.4 Health Effects Models

The area of radiogenic health effects modeling is one that has undergone considerable growth during the last decade. More is known about the effects of radiation exposure than those of most other agents of biological stress. However, there is considerable controversy concerning the effects of low-level ionizing radiation in spite of the fact that no reliable studies have been able to show a statistically significant increase in latent cancer risk at low doses and low-dose rates. The reader is referred to the 1980 report of the National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR III)[24] for the most up-to-date and authoritative information on this subject. The risk estimators derived from the BEIR III report concerning exposure to low-level low linear energy transfer (LET) radiation are summarized in Tables 2 and 3 and are the basis for the estimates of latent cancer risk from low LET radiation in this analysis. Estimates of the risk from high LET exposure (for example, to the progeny of Rn-222) are also based on guidance given in BEIR III. The risk estimators used for lung and bone cancer resulting from Rn-222 emissions from uranium mines and mills were 70 and 4 deaths per 10^6 person-rem, respectively, and were derived by using the BEIR III linear model.

It must be stressed that all such estimates are potential because the actual risks may be much smaller, and for low LET radiation could include zero risk (Ref. 24, p. 187).

To identify possible counterpoint to the current health effects models used in this assessment, it is noted that a recent monograph[25] has concluded that exposure to radiation up to certain levels may act as a stimulant to biological systems and result in increased life expectancy, greater reproduction, reduced mortality, and so forth. This hypothesis, called radiation hormesis, is supported by over 1,000 documented studies with plants and animals. The studies with mammals indicate that radiation doses of about 10 rem per year represent an optimum for maximum benefit. If radiation exposures did in fact increase life expectancy, then the observed increased risk of cancer could be consistent with such a hypothesis, since cancer rates increase exponentially in old age. Although the radiation biology community has not yet carefully examined this hypothesis, this new information will be reviewed in the years ahead. If proven, this hypothesis will radically alter the health effects estimates presented here and elsewhere, because low-level radiation doses would result in positive benefits in terms of a long healthy life perhaps at the cost of a greater lifetime risk of death from nonradiogenic cancer.

As yet no human data are available which clearly define the genetic risks of low-level radiation exposure, not even from the large group of survivors in Hiroshima and Nagasaki who were exposed to very high levels of radiation. As a result, the BEIR III authors found it necessary to rely primarily on animal data, which now span many consecutive generations of exposed animals. The genetic risk estimates derived from the BEIR III report are summarized in Table 4 and were used in this analysis. These estimates represent expected genetic risk from exposure of one generation of parents over subsequent generations of offspring (total time of several hundred years).

Table 2 Total latent cancer mortality per 10^6 person-rem*

Dose/dose rate	Male	Female	Both**
Acute exposure			
≤ 25 rem	144	158	151
Continuous exposure			
≤ 12 rem/yr			
General public	107	123	115
Occupational workers (20-65 yrs)	81.8	113	97.6

*Based on Tables V-I6 and V-I9, BEIR III (Ref. 24). All estimates should be rounded to two significant figures to avoid the unwarranted impression of great precision.

**"Both" assumes equal numbers of both sexes (usually not so for occupational workers).

Table 3 Organ-specific cancer mortality per 10^6 person-rem

	Acute exposure (< 25 rem)			Continuous exposure (≤12 rem/yr)*					
				General population			Occupational workers		
Type of cancer	Male	Female	Both**	Male	Female	Both**	Male	Female	Both**
Thyroid	5.2	13.0	9.1	3.7	10.0	6.9	2.7	9.1	5.9
Lung	39.7	33.1	36.4	28.6	25.4	27.0	20.7	23.2	22.0
Breast	~0	25.4	12.7	~0	19.5	9.8	~0	17.8	8.9
Esophageal	3.4	3.1	3.3	2.5	2.4	2.5	1.8	2.2	2.1
Stomach	15.1	14.6	14.9	10.9	11.3	11.1	7.9	10.3	9.1
Intestinal	7.0	6.9	7.0	5.0	5.3	5.2	3.6	4.8	4.2
Liver	9.2	7.8	8.5	6.6	6.0	6.3	4.8	5.5	5.2
Pancreatic	10.8	10.0	10.4	7.7	7.7	7.7	5.6	7.0	6.3
Urinary	3.9	4.5	4.2	2.8	3.5	3.2	2.1	3.2	2.6
Lymphoma	2.6	2.3	2.5	1.9	1.7	1.8	1.3	1.6	1.5
Leukemia and bone***	27.4	18.6	23.0	22.7	16.1	19.4	20.9	15.7	18.3
Other	20.0	18.3	19.2	14.3	14.1	14.2	10.4	12.9	11.7
Totals	144.0	158.0	151.0	107.0	123.0	115.0	81.8	113.0	97.6

*Lifetime exposure for general population; exposure between ages 20 and 65 for occupational workers.

**"Both" assumes equal numbers of both sexes (usually not so for occupational workers).

***Bone represents approximately 2.2% of total for leukemia and bone cancer combined.

Source: Based on Tables V-I4 to V-I6, BEIR III (Ref. 24).

Table 4 Genetic risk per 10^6 liveborn*

Genetic effect	Range	Geometric mean
Autosomal dominant and X-linked disorders	40-200	89 (factor of ±2.2)
Irregularly inherited disorders	20-900	130 (factor of ±6.7)
Overall risk	60-1,100	$\Sigma = 220$

*Assuming one live birth per person per generation surviving to reproduce (zero population growth), the risks are approximately the same per 10^6 person-rem (high or low LET radiation).

Source: Based on Table IV-2, BEIR III (Ref. 24).

2.1.5 Uncertainties in Radiation Risk Assessment

The uncertainties in analyses such as those presented in this report can be quite large or fairly small, depending on their source. For example, extrapolation of health effects into the future, by necessity, results in very large uncertainties (one or more orders of magnitude, depending on how distant the upper limit of the integral is). All these estimates are only semiquantitative in nature and are based on considerable professional judgment. On the other hand, estimates of deaths (both radiological and accidental) among miners can reasonably be based on recent experience and are probably accurate to within a factor of 2 or 3.

Large uncertainties in predictions of future risk come from several sources, of which the following are of major importance:

1. It is, and always will be, impossible to accurately estimate future population dose commitments because it is impossible to accurately project the size of the populations at risk.

2. The health risks associated with radiation exposure (cancer and genetic effects) change with time as societies change. Such changes cannot be predicted over long periods.

Let us now examine some of the reasons for these statements. Consider, for example, that the U.S. Bureau of the Census claims about ±25% accuracy in its best population projections over the next 50 years provided "there will be no large-scale war, widespread epidemic, or other major catastrophe."[26] Projections beyond 50 years are obviously far less likely to be accurate and meaningful, although they can be made based on selected assumptions. For more discussion in this area, see References 27-36.

The easiest course is to assume that everything will stay basically the same as it is today, allowing the U.S. population to grow to 300 million over the next 50 years, and remain stable for the rest of this millenium. Although experience has proven beyond any reasonable doubt that the only thing that is constant is change, if one is willing to pretend a little, perhaps it is possible to estimate the U.S. population to within a factor of 3 or 4 during the next 100 years. It may even be possible to estimate the U.S. population over the next 1,000 years to within a factor of 5 or 10.

The second major source of uncertainty comes from the recognition that the potential risks from low-level radiation are strongly dependent on the characteristics of the exposed population and the capabilities of future medical practice. Consider the differences between the 1900 and 1970 U.S. populations in terms of mortality risks. As shown in Table 5, deaths from cancer and cardiovascular disease were not as great in 1900 as they were in 1970. Therefore, the somatic risks from radiation exposure were probably also less per person-rem, because cancer, whatever the causes, is primarily a disease of old age. In 1900, life expectancy at birth was about 45 years; by 1970, it had increased to over 70 years. Because more people survive diseases that previously would have killed them before they reached age 40, the lifetime risk of radiogenic

Table 5 Comparison of causes of mortality in U.S. populations, 1900 and 1970

Cause of death	Deaths/100,000 population 1900	Deaths/100,000 population 1970	Change in risk of mortality by 1970
Tuberculosis	194.4	2.6	Factor of 75 lower
Typhoid and paratyphoid fever	31.3	0.05	Factor of 600 lower
Diphtheria	40.3	0.05	Factor of 800 lower
Cancer	64.0	162.8	Factor of 2.5 higher
Major cardiovascular and renal diseases	345.2	496.0	Factor of 1.4 higher
Influenza and pneumonia	202.2	30.9	Factor of 6.5 lower
Gastritis, duodenitis, enteritis, and colitis	142.7	0.6	Factor of 240 lower
Accidents (including motor vehicle)	72.3	56.4	Factor of 1.3 lower
Other major diseases	58.4	35.1	Factor of 1.7 lower
Overall	1,150.8	784.4	Factor of 1.5 lower

Source: Reference 37.

cancer has gradually increased since 1900, and may continue to do so until some means is found to prevent or cure it.[38-46] We can hope the future will bring change for the better, but in this analysis, it will be assumed that conditions will remain almost the same as they are today for the next century. Beyond that, it is probable that the risks from radiogenic cancer and genetic effects will be much less than they are today because of medical and technological advances. The uncertainties in current health effects modeling are probably about a factor of 5 or 10, but may increase with the time integral to one or more orders of magnitude during the next millenium. The competing risks associated with future catastrophic events such as an uncontrolled Greenhouse Effect would be an added source of uncertainty in estimating the risks of low-level radiation exposure (see Sec. 3.3.1 for more details). These uncertainties can only be imagined and will not be considered in this analysis. Additional discussions of these problems can be found in other works.[4,13,27-34,36,47,48]

2.1.6 Collective Population Dose Commitments and Potential Health Impacts

2.1.6.1 Radiation Risks to the General Public

The detailed results of the calculations using the radiological source terms and models just discussed are presented in Tables 6 and 7. In general, only those radionuclides that could result in dose commitments in excess of about 1 person-rem are identified in the tables. The rest are summed under the category "Other." The combined potential health impacts of radionuclides in both gaseous and liquid effluents are summarized in Table 8.

H-3, C-14, Kr-85, and I-129 also contribute to exposure of populations outside the United States. However, most of the world population dose commitments during the next 1,000 years from H-3, I-129, and Rn-222 would be due to the first-pass exposure of the U.S. population, and the population dose would not significantly change if the world population were considered. In the case of C-14, however, the world population dose would be about 5 times greater than that to the United States for the next 100 years, and about 10 times greater than that to the United States over the next 1,000 years. Similarly, the Kr-85 population dose to the world would be about 20 times greater than that to the United States. Examination of Tables 6 and 7, however, shows that these increases could result in about 60 to 70% increases in the total cancer risk and 140 to 230% increases in the genetic risks shown in Table 8. Given the much larger uncertainties in projecting health impacts on other populations in the world (because of differences in life expectancies, spontaneous cancer mortality, and competing risks), the relatively conservative estimates presented for the United States could be considered to reasonably reflect the cancer risk to the entire world from the U.S. nuclear fuel cycle.

The risk of developing cancer is, in general, greater than the cancer mortality because some cancers (for example, thyroid) have a relatively small risk of mortality. BEIR III indicates that the overall cancer incidence for external or whole-body exposure is about 1.5 to 2 times higher than mortality.[24] However, because a large fraction of the fuel-cycle cancer mortality is from bone and lung cancer (from Rn-222 releases), which have an assumed 100% mortality in the BEIR III models, the overall fuel-cyle incidence should not be much greater than the mortality.

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Table 6 Collective U.S. general population dose commitments and potential health impacts resulting from the release of gaseous radioactive effluents from normal operations of the nuclear fuel cycle per GW(e)-yr*

		Dose commitments (person-rem)					Potential health impacts	
Source of dose commitment	Nuclide	Total body	Bone	Lung	Thyroid	Total body-risk equivalent	Potential latent cancer mortality	Potential genetic effects
Uranium mines	Rn-222	53-190	720-2,600	520-1,900	-	210-740	0.063-0.22	0.012-0.042
Uranium mills and tailings	Rn-222	15-120	200-1,600	150-1,200	-	58-460	0.033-0.15	0.013-0.036
	Ra-226	42	45	< 1	-	42		
	Other	0.83	28	31	-	9.3		
Light-water-cooled nuclear power plants	H-3	16	-	-	-	16	0.011-0.013	0.020-0.024
	C-14	54-71	-	-	-	54-71		
	Co-60	11	-	-	-	11		
	Kr-85	< 1	-	-	-	< 1		
	Xe-133	4.8	-	-	-	4.8		
	I-131	< 1	< 1	< 1	61**	< 1		
	Other	6.4	13	~ 1	~ 1	6.8		
Fuel reprocessing plants	H-3	230	-	-	-	230	0.050-0.055	0.092-0.10
	C-14	130-170	-	-	-	130-170		
	Kr-85	28	-	-	-	28		
	I-131	< 1	< 1	< 1	120**	< 1		
	Cs-134	9.9	-	-	-	9.9		
	Cs-137	15	-	-	-	15		
	Other	2.8	39	1.4	< 1	~ 3.3		
Geologic repository	I-129	5.5	-	-	440	33	0.0040	0.0012
100- to 1000-yr totals							0.16-0.44	0.14-0.20

*Totals are for time periods of 100 and 1000 years into the future when ranges are given. The impacts of all other fuel-cycle facilities are insignificant by comparison and result in population dose commitments of less than 1 person-rem each.

**A dose-effectiveness factor of 1/10 is applied in computing thyroid cancer risk from exposure to I-131 because I-131 is only about 10% as effective as X-rays, gamma rays, or other iodine isotopes (see, for example, Ref. 20, pp. 9-26, and Ref. 24, pp. 353-354).

Table 7 Collective U.S. general population dose commitments and potential health impacts resulting from the release of liquid radioactive effluents from normal operations of the nuclear fuel cycle per GW(e)-yr*

		Dose commitments (person-rem)					Potential health impacts	
Source of dose commitment	Nuclide	Total body	Bone	Lung	Thyroid	Total body-risk equivalent	Potential latent cancer mortality	Potential genetic effects
UF_6 conversion plants	Ra-226	120	130	< 1	< 1	125	0.038	0.026
Light-water-cooled nuclear power plants	H-3	5.3	-	-	-	5.3	0.0006	0.0014
	I-131	< 1	< 1	< 1	19**	< 1		
	Cs-137	~ 1	-	-	-	~ 1		
Totals							0.039	0.027

*The impacts of all other fuel-cycle facilities are insignificant by comparison and result in population dose commitments of less than 1 person-rem each.

**A dose-effectiveness factor of 1/10 is applied in computing thyroid cancer risk from exposure to I-131 because I-131 is only about 10% as effective as X-rays, gamma rays, or other iodine isotopes (see, for example, Ref. 20, pp. 9-26, and Ref. 24, pp. 353-354).

Table 8 Summary of potential health impacts among the U.S. general population from normal operations of the nuclear fuel cycle per GW(e)-yr*

Source of dose commitment	Potential latent cancer mortality	Potential genetic effects
Uranium mines	0.063-0.22	0.012-0.042
Uranium mills and tailings	0.033-0.15	0.013-0.036
UF$_6$ conversion plants	0.038	0.026
Light-water-cooled nuclear power plants	0.012-0.014	0.021-0.025
Fuel reprocessing plants	0.050-0.055	0.092-0.10
Geologic repository	0.0040	0.0012
Totals	0.20-0.48	0.17-0.23

*Where ranges are given, the values represent impacts for 100- and 1,000-year environmental dose commitments, respectively. Impacts from other facilities are too small to change the totals.

Finally, lest it be forgotten, a radiological risk is associated with almost any human activity, including tilling the soil (Rn-222 releases and resuspension of naturally occurring potassium-40 (K-40) to the air where it can be inhaled); congregating for scientific conferences (K-40 gamma rays from internal depositions in attendees); building tight energy-efficient homes, particularly with brick and stone (K-40 and Rn-222 releases from the building materials); or generating electricity by coal combustion (principally uranium-238 (U-238), U-235, thorium-230 (Th-230), radium-226 (Ra-226), Rn-222, and K-40 emitted with the fly ash as discussed in Sec. 3.1.1). These releases may have public radiological risks that are comparable to those from normal operation of the nuclear fuel cycle.[35,49-55]

Furthermore, Cohen[56] has calculated that, over geologic times, the nuclear fuel cycle may even save hundreds of human lives, resulting in a negative health risk per GW(e)-yr. This idea, which surely deserves a special title (the "Cohen Effect," analogous to the "Suess Effect" for coal combustion),* is based on the fact that the uranium fuel cycle removes U-235 and U-238 from the uranium ore for use as fuel, leaving the balance of the decay chain headed by Th-230. Because Th-230 has a half-life that is only about 0.002% that of U-238, the emanation of Rn-222 from uranium mill tailings is greatly reduced over billions of years relative to undisturbed ore, since erosion of the continent will continually bring the uranium ore to the surface of the earth. Such calculations over billions of years into the future must be considered with caution because of the uncertainties in populations and cancer risk over long periods. However, they should give second thoughts to those who calculate health risks associated with the uranium mill tailings and the nuclear fuel cycle over billions of years.

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*H. E. Suess, "The Radioactivity of the Atmosphere and Hydrosphere," Annual Review of Nuclear Science 8, 243, 1958.

2.1.6.2 Occupational Radiation Risks

With regard to occupational radiation risks from the nuclear fuel cycle, the GESMO and Table S-3 (10 CFR Part 51) analyses provide a detailed current assessment of occupational dose commitments.[6,8-10] These estimates and the potential health risks are summarized in Table 9. Because most of the occupational dose commitments are from whole-body exposures to external radiation sources, no breakdown by radionuclide is practical. Only in the case of uranium miners do the risks from internally deposited radioactivity (short-lived Rn-222 progeny in the bronchi of the lungs) become of great importance. It should be noted that the major source of genetic risk among workers in the nuclear fuel cycle comes from nuclear power plant exposures. It is also worth noting that the total cancer and genetic risks over the next century for the nuclear fuel cycle (per GW(e)-yr) are almost equally divided between workers (0.25 and 0.17, respectively) and the general public (0.20 and 0.17, respectively). However, because of the small number of nuclear workers, the average individual risks for workers or their descendants are much higher than for the general public, although still small compared with the normal risks of these effects among non-nuclear workers, or careers associated with exposures to nonradiological agents (for example, vinyl chloride, asbestos, and benzene).[57,78]

A recent report to the President indicates that occupational exposure to such carcinogens is believed to be a factor in more than 20% of all cases of cancer, while an unknown number of persons are at risk because of the seepage of carcinogenic chemicals into domestic water supplies from waste dumps and other types of exposure.[57]

2.1.6.3 Radiological Health Risks From Accidents

The potential health risks resulting from catastrophic accidents in the nuclear fuel cycle appear to be dominated by the risks associated with only a few of the most serious potential accidents in nuclear power plants.[58] In particular, the Reactor Safety Study showed that most of the total risk of all potentially serious nuclear accidents depends on only a few types of accidents in either pressurized water reactors or boiling water reactors. Even though the probabilities of occurrence for these particular types of accidents are estimated to be exceedingly small, the potential health consequences could be very high during such an accident, approaching in total numbers an amount equal to the annual death rate of U.S. highways.

The Reactor Safety Study estimated that the potential risk of cancer mortality from nuclear power plant accidents was 0.02 deaths per year of operation for a 1,000-MW(e) plant, and that the risk of early or acute fatalities from high radiation exposure was more than one hundredfold smaller. These estimates were based on an application of probabilistic risk assessment methodology and contain substantial uncertainties. An independent peer review of the Reactor Safety Study, entitled "Risk Assessment Review Group Report to the U.S. Nuclear

Table 9 Collective occupational dose commitments and potential health impacts of the nuclear fuel cycle per GW(e)-yr

	Dose commitments (person-rem)					Potential health impacts*	
Source of dose commitment	Total body	Bone	Lung	Thyroid	Total body-risk equivalent	Potential latent cancer mortality	Potential genetic effects
Uranium mines	88	360	1,400	250	470	0.096	0.019
Uranium mills	88	440	1,000	40	370	0.076	0.019
UF$_6$ conversion plants	< 1	10	6.9	< 1	2.3	0.0005	∼ 0
Enrichment plants	< 1	5.9	14	< 1	6.2	0.0013	∼ 0
UO$_2$ fuel fabrication plants	12	4.4	450	< 1	130	0.027	0.0026
Light-water-cooled nuclear power plants	560	-	-	-	560	0.046	0.12
Irradiated fuel storage	3.6	-	-	-	3.6	0.0003	0.0008
Reprocessing	28	-	-	-	28	0.0023	0.0062
Transportation	1.8	-	-	-	1.8	0.0001	0.0004
Waste management	< 1	-	-	-	< 1	∼ 0	∼ 0
Totals						0.25	0.17

*Based on an essentially all-male population of workers.

Sources: References 6 and 8-10.

Regulatory Commission," pointed out: "We are unable to define whether the overall probability of a core melt given in WASH-1400 is high or low, but we are certain the error bands are understated."*

Uncertainties in the risk estimates arise from such varied sources as incompleteness of the data base for component and system failure rates, and uncertainties associated with human error and operator intervention, with the data base for severe external events (for example, earthquakes), and with the mathematical modeling of complex physical phenomena associated with accident sequence events. These sources of uncertainty include both pessimistic (conservative) and optimistic (nonconservative) factors so that there is at least a tendency for them to balance to some extent.

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*H. W. Lewis et al., "Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission," USNRC Report NUREG/CR-0400, September 1978.

The risk estimate for cancer mortality included the application of so-called dose and dose-rate effectiveness factors, which reduced the "upper bound" risk by a factor of 2. In the absence of BEIR III guidance, it is felt that, although there are sound radiobiological reasons for these factors (for example, biological repair mechanisms), it is prudent to raise the WASH-1400 risk estimate to 0.04 deaths per GW(e)-yr and this is the value entered in the summary, Table 14. It is important to note, that even if the catastrophic risks of nuclear power are as much as 100 times greater than the 0.02 death estimated in the Reactor Safety Study, catastrophic accidents could result in about two deaths (acute fatalities and latent cancers) per GW(e)-yr. This increase, combined with those from normal operations, would make the total risks from the nuclear fuel cycle approximately equal to the low end of the range of total mortality risks from the coal fuel cycle. Furthermore, as will be shown later, these risks are small in relation to the everyday, more familiar risks (for example, cigarette smoking, travel, and recreation).

2.1.6.4 Perspectives on Radiation Risk

It lends perspective to compare the potential health impacts of the nuclear fuel cycle just calculated by comparing them with other more commonplace risks, even though many of these risks result from voluntary individual activities. It must also be kept in mind that the lower-bound radiological risks, particularly those among the public, may actually be zero for low doses and dose rates of low LET radiation. The following comparisons are not intended to be all inclusive, and other comparisons are possible. The calculated health risks among the general public associated with these exposures are for the U.S. general population. No attempts were made to quantify equities and temporal and spatial distributions of risks because these quantifications are presently beyond the state of the art (see Sec. 4 for further discussion of these issues).

Naturally occurring background radiation is the first comparison shown in Table 10. The major sources for these doses are cosmic rays and terrestrial radioactivity, which result in both external and internal exposures.[24,59,60] Similar risks to the same population from other common sources of radiation exposure, such as medical X-rays and color-television viewing, are the comparisons shown next in Table 10.[24,55,60]

Table 11 shows comparisons of the naturally occurring risks of health impacts in the U.S. population.[61,62] Finally, comparisons between the radiological mortality risks to occupational workers and more familiar mortality risks[63] (generally from causes that lead to larger losses of life expectancy than does radiogenic cancer) are presented in Table 12.

These comparisons clearly demonstrate that the lifetime risks associated with the nuclear fuel cycle are extraordinarily small for the U.S. general population when compared with other everyday risks people face with relatively mild trepidation. Some possible reasons for the apparent differences in public and expert perceptions of these risks are presented in Section 4. However, even if all the electricity in the United States were to be produced by the nuclear fuel cycle, the additional risk would represent less than a 0.01% increase in the risk of mortality from all other causes.

Table 10 Comparisons of the potential health risks among the U.S. general population from the nuclear fuel cycle per GW(e)-yr with similar risks from other sources of radiation exposure

		Potential health risks	
Source of radiation exposure	Population total body-dose commitments (person-rem)	Potential latent cancer deaths	Potential genetic effects
Average for U.S. from nuclear fuel cycle for 100 yr per GW(e)-yr	1,700*	0.20	0.17
Average for U.S. from natural background radiation (~ 102 mrem/yr)	22,000,000	2,500	4,800
Average for Denver, CO, from natural background radiation (~ 180 mrem/yr)	180,000	21	40
Average for U.S. from television viewing (~ 1 mrem/yr from low-energy X-rays)	220,000	25	48
Average for U.S. from diagnostic X-rays (~ 72 mrem/yr)	16,000,000	1,800	3,500

*This includes both external total body doses and specific organ doses from internally deposited radionuclides. The genetically significant dose is about 750 person-rem.

Sources: References 24, 59, and 60.

Table 11 Normal annual risk of mortality among the U.S. general population

Source of risk	Risk of mortality
All causes of death	2,100,000
Major cardiovascular diseases	1,100,000
Total cancers	400,000
Smoking cigarettes	300,000
All accidents	120,000
Automobile driving accidents	57,000
Falls	17,000
Fires and hot substances	7,000
Drowning	6,200
Accidental poisoning by drugs and medications	2,400
Air travel accidents	1,500
Accidental electrocution (regardless of how the electricity is generated)	1,100
Railway travel accidents	660
Lightning	88
Nuclear fuel cycle per GW(e)-yr	0.24*
Substitution of a coal-fired plant for a nuclear plant (based on estimates in the next section for the entire fuel cycle)	6.1-12**

*Would approximately triple if risks to workers were included.
**Would increase by about 20 to 30% if risks to workers were included.

Sources: References 61 and 62.

Table 12 Lifetime mortality risks numerically equivalent to the potential risks of mortality associated with occupational radiation exposures

Type of activity	1 rem	25 rem (emergency)*	45 rem/lifetime**
Smoking cigarettes	1 carton	25 cartons	0.5 cigarette/day***
Drinking wine	66 bottles	33 bottles/yr***	1 bottle/wk***
Automobile driving	6,600 miles	3,300 miles/yr***	5,900 miles/yr***
Commercial flying	33,000 miles	17,000 miles/yr***	30,000 miles/yr***
Rock climbing†	3.3 hours	10 days	18 days
Canoeing†	1.6 days	1.3 months	2.4 months
Being a man aged 60	1.8 days	1.5 months	2.7 months

*25 rem in one exposure.
**1 rem per year for 45 years (ages 20 to 65).
***Use--50 years (ages 20 to 70).
†Activity--8 hours per day.

Note: One bottle equals about 0.8 liter, 1 mile equals about 1.6 km.

Source: Reference 63.

2.2 Other Potential Impacts of the Nuclear Fuel Cycle

2.2.1 Nonradiological Risks From Accidents

Some additional risks (other than cancer and genetic effects) involved in occupational activities (mostly mining) come from estimates in the latest National Academy of Sciences (NAS) report by the Committee on Nuclear and Alternative Energy Systems (CONAES).[4] This analysis indicates the following mortality risks per GW(e)-yr: (1) mining, 0.2 death; (2) processing, 0.001 death; (3) transport, 0.01 death; and (4) power generation, 0.01 death, or a total of about 0.22 accidental death per GW(e)-yr. A similar CONAES estimate for total accidental injuries per GW(e)-yr for the entire nuclear fuel cycle is 20 injuries per GW(e)-yr. A value of 7 is shown in a 1973 Council on Environmental Quality (CEQ) report[64] (Table A-1), which gives the following breakdown on accidental injuries per GW(e)-yr: (1) mining, 4.6; (2) processing (UF_6, enrichment, fabrication, reprocessing, waste management), 0.76; (3) transportation, 0.06; and (4) light-water reactors, 1.7. Clearly, most of these injuries are associated with accidents in uranium mines (that is, the pattern follows the one for accidental deaths).

2.2.2 Potential Impacts of the Nuclear Fuel Cycle on Ecosystems

The 1979 CONAES report concluded that the potential ecological impacts of the nuclear fuel cycle are similar in nature to those in the coal fuel cycle from coal mining. However, the quantitative impacts per GW(e)-yr would be much smaller because the fuel needs and mining requirements are much less than those for the coal fuel cycle.[4]

The CONAES Risk and Impact Panel concluded that radiation risk to biota would be insignificant as long as individual members of the public were protected.* This finding is consistent with the NAS BEIR Committee conclusions.[24,60]

In addition to the principal concerns associated with potential radiation impacts from the nuclear fuel cycle, the NRC and its predecessor, the U.S. Atomic Energy Commission, have summarized the other major impacts of the nuclear fuel cycle stated in 10 CFR Part 51 (see Ref. 9). Because 10 CFR Part 51 omits impacts from reactor operations, it was necessary to extract them from Reference 6 (GESMO Tables S(A)-1 and IV J(E)-17). Major items of interest are summarized in Table 13. The environmental impacts, including thermal and chemical effects, are generally insignificant for modern nuclear facilities that are properly designed and sited.

2.2.3 Risks Associated With Proliferation and Terrorism

Although this assessment does not address the potential health risks associated with proliferation of nuclear weapons and terrorism, these concerns have been evaluated by CONAES.[4] This committee is split on the issue of proliferation, and no one can yet reasonably quantify the risks.

CONAES carefully examined the sociopolitical question of linkage between commercial nuclear power and the risk of proliferation of nuclear weapons (see especially pp. 392-415 of Ref. 4). It was concluded that even a cessation of commercial nuclear power could not stop proliferation, because other less expensive alternatives for producing weapon material (for example, that used by India) are readily available.

However, CONAES argued for the use of political barriers to reduce the rate of proliferation, with the belief that slower proliferation would allow institutions to evolve to the point where the risk of nuclear war would be comparable to or less than it is today. These barriers would include strengthening of the Non-Proliferation Treaty and placing fuel cycle operations involving weapons-usable material under international control. CONAES concluded that a potential linkage may exist between expansion of commercial nuclear power in the world and the risk of nuclear war, but it is at most a weak linkage. Thus, in time, other sociopolitical controls must be developed or proliferation could occur with or without a commercial nuclear power program.

CONAES noted that many energy sources face the terrorist threat. Examples are dams and fuel-storage facilities for oil, natural gas, liquefied fuels, and so forth. However, the risks of terrorist attacks on nuclear facilities (or diversion of nuclear materials) are easier to control than those on the other sources because the areas are smaller and the number of personnel involved is less, making security tighter and facilities more defensible. Levels of security now required in nuclear facilities are not greatly different from those used in high-security projects, such as the Manhattan Project or in the protection of the gold at Fort Knox, which have succeeded in their objectives. Historically, personnel clearance for employment has been used routinely in the past without

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*Personal communication from Dr. James Crow, Chairman of the Risk and Impact Panel, August 13, 1982.

Table 13 Summary of other environmental considerations for the nuclear fuel cycle per GW(e)-yr

Natural resource use	Supporting nuclear fuel cycle	Light-water-cooled reactors	Total (approximate)
Land (acres)			
Disturbed	28	10	38
Committed	16	0.2	16
Water (millions of gallons)			
Discharged to air	200	8,180	8,400
Discharged to water bodies	13,900	8,180	22,000
Discharged to ground	160	-	160
Plant effluents to atmosphere (metric tons)			
Sulfur oxides	5,500	120	5,600
Nitrogen oxides	1,490	69	1,600
Hydrocarbons	18	5.0	23
Carbon monoxide	37.3	4.5	42
Particulates	1,443	16	1,500
Fluoride	0.84	-	0.84
Chloride	0.018	-	0.018
Plant effluents to water bodies (metric tons)			
Sulfates	12.4	3,470	3,500
Nitrates	32.3	-	32
Fluorides	16.1	-	16
Calcium	6.8	-	6.8
Chloride	10.6	297	310
Sodium	15.1	-	15
Ammonia	12.5	-	13
Iron	0.5	-	0.5
Thermal (billions of British thermal units [Btu])	5,079	66,900	72,000

Note: 1 acre equals 0.405 hectare; 1 gal equals 3.8 liters; 1 metric ton equals 2,240 lb; 1 Btu equals 252 gm-calories.

Source: Reference 6.

significant compromise of civil liberties. Thus, it is reasonable to believe that the same objective can be reached for the commercial nuclear fuel cycle. Furthermore, CONAES concluded that high-security protection would add little to the cost of nuclear power.[4]

2.3 Summary and Conclusions

The health impacts of the nuclear fuel cycle per GW(e)-yr estimated in this assessment are summarized in Table 14. Although any breakdown of potential health impacts represents an unusual mixture of items, it is clear that the potential impacts on the general public and occupational workers for the entire nuclear fuel cycle are small in absolute numbers, and in relation to other everyday risks. Although one may argue that cancer risks to occupational workers are accepted voluntarily and the public's cancer risks are involuntary in nature, this distinction changes neither the pain and economic distress suffered nor the cost to society in the loss of one of its members because of a premature death (see Sec. 4 for more discussion on this issue). Furthermore, occupational risks, which must be borne by any worker regardless of occupation, may be dictated by forces (for example, economics, chance, and tradition) beyond the control of most workers, obscuring the distinction between the voluntary or involuntary nature of the risks. In that respect, the total cancer risks may be additive. In addition, other potentially greater occupational cancer risks (for example, those resulting from exposure to industrial solvents and dusts), have not been included because data concerning these risks are not readily available. However, the 1980 Report to the President by the Toxic Substances Strategy Committee indicates that occupational exposure to carcinogens (primarily nonradiological) may be a factor in more than 20% of all cases of cancer.[57]

It is also interesting to note the extent of the impact of the coal fuel cycle on the nuclear fuel cycle if (using the estimates from Table 14 and Sec. 3 of this report) it is assumed that the 0.056 GW(e)-yr of electric power needed to operate the nuclear fuel cycle per GW(e)-yr comes entirely from coal power. Because most of this energy is currently used for uranium enrichment, and much of the power is, in fact, derived from coal combustion, such additions are probably not unreasonable.

It should now be obvious that it is not possible to live without being at risk. Yet needless risk can and should be avoided if the incremental reduction in risk can justify the expenditure of public resources. This important criterion for making such decisions was best stated by the NAS Committee on the Biological Effects of Ionizing Radiation:

> The public must be protected from radiation but not to the extent that the degree of protection results in substitution of a worse hazard for the radiation avoided. Additionally, there should not be attempted the reduction of small risks even further at the cost of large sums of money that, spent otherwise, would clearly produce greater benefit. (Ref. 60, p. 2)

The environmental impacts of the chemical and thermal releases summarized in Table 13 are not significant for a well-sited nuclear power plant, and as noted by CONAES, the potential ecological impacts of the nuclear fuel cycle Per GW(e)-yr are similar in kind but, with the exception of thermal releases,* much smaller than those of the coal fuel cycle.[4]

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*The overall thermal efficiency of a modern coal-fired plant is somewhat higher than that of a nuclear power plant. As a result, the thermal releases to the hydrosphere are less for a modern coal-fired plant.

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Table 14 Summary of potential health risks among the total U.S. population per GW(e)-yr for the nuclear cycle

Source of risk	Potential latent cancer mortality		Occupational accidents and diseases		Potential latent cancer incidence		Potential genetic effects in future generations		Total mortality	Total injury and disease
	Occupational (A)	General public† (B)	Mortality (C)	Nonfatal cases (D)††	Occupational (E)	General public† (F)	Occupational (G)	General public† (H)	(A+B+C) (I)†	(D+E+F+G+H) (J)††
Uranium mining	0.096	0.063-0.22	0.2	4.6-13	~ 0.1	~ 0.07-0.25	0.019	0.012-0.042	0.36-0.52	4.8-13
Processing*	0.10	0.071-0.19	0.001	0.76-2.1	~ 0.1	~ 0.08-0.21	0.021	0.039-0.62	0.17-0.29	1.0-3.1
Power generation	0.046	0.012-0.014	0.01	1.7-4.8	0.069	0.022-0.025	0.12	0.021-0.025	0.068-0.070	1.9-5.0
Transportation	0.0001	**	0.01	0.06-0.17	0.0002	**	0.0004	**	0.01	0.061-0.17
Reprocessing	0.0023	0.050-0.055	**	**	0.0035	0.090-0.099	0.0062	0.092-0.10	0.052-0.057	0.19-0.21
Waste management	**	0.0040	**	**	**	0.007	**	0.0012	0.004	0.008
Catastrophic accidents	**	0.04	**	**	**	~ 0.07	**	0.08	0.04	0.15
Subtotals	0.25	0.24-0.52	0.22	7-20	~ 0.27	~ 0.33-0.66	0.17	0.25-0.31	0.70-0.99	8.1-22
Production of 56 MW(e)-yr of power by coal combustion to operate the nuclear fuel cycle (per GW(e)-yr); from estimates in Section IV.										
	~ 0.015	0-0.073 (0.3-0.6 deaths from air pollution)	~ 0.13	~ 5.1	~ 0.02	0-0.13 (3.7-6.7 nonfatal injuries and diseases)	> 0	> 0	0.47-0.82	8.8-12
Totals	~ 0.51-0.86 fatal cancers (0.3-0.6 deaths from air pollution)		≥ 0.37	≥ 12-25	≥ 0.62-1.1 cancer cases (3.7-6.7 nonfatal injuries and diseases among public)		≥ 0.42-0.48 potential genetic effects		1.2-1.8	17-34

†The range indicated in columns B, F, H, and I represents the estimates for 100- and 1,000-year environmental dose commitments.

††The range indicated in columns D and J is largely due to differences in the assumed value for the fraction of uranium mined by strip mining, rather than underground mining.

*Includes uranium milling, UF_6 conversion, enrichment, and fuel fabrication.

**These values are expected to be small relative to those presented, but are currently not available.

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3 POTENTIAL HEALTH AND ENVIRONMENTAL IMPACTS OF THE COAL FUEL CYCLE

The coal fuel cycle has associated with it steps similar to those of the nuclear fuel cycle: resource recovery, fuel preparation, transportation, fuel combustion, and waste disposal. However, the impacts for each step may be much different in character and absolute numbers. Major differences in quantities of fuel required per reference reactor year (RRY) result from the fact that a much greater mass of coal must be mined and transported and more wastes must be disposed of than for the nuclear fuel cycle. For example, currently about 200 to 300 metric tons of U_3O_8 are required to produce a gigawatt-year of electric energy. Thus, for ore containing 0.11% U_3O_8, about 180,000 to 250,000 metric tons of uranium must be mined to produce enough U_3O_8 for an RRY. This ore is then shipped a relatively short distance to a uranium mill where about 90% of the uranium is recovered for use as reactor fuel. This relatively small amount of material (yellow cake) is then transported relatively long distances throughout the balance of the fuel cycle. The balance of the ore becomes uranium mill tailings waste, which is generally disposed of at the mill, although much of it could be disposed of in below-ground burial at strip mines or worked-out underground mines, usually in fairly desolate areas of the western United States.

Coal, on the other hand, must be mined in huge amounts, about 3 million metric tons per RRY, and transported relatively long distances for power generation, leaving about 300,000 metric tons of solid wastes per RRY at the power station for disposal, usually near urban areas.

In the following sections, the discussion will highlight similarities and differences between the two fuel cycles beginning with comparisons of radiological impacts and ending with nonradiological impacts that are quite different (for example, acid precipitation and acid mine drainage, potential impacts of stable toxic trace metals and carcinogens, the Suess Effect, and the Greenhouse Effect).

As a result of the controversial nature of coal fuel cycle impacts, the author has attempted to pull together numerous sources of information that are currently not available in a few good references. As a result, it may appear that more detail regarding the potential impacts of the coal fuel cycle is provided than for the nuclear fuel cycle. However, a great deal more detailed information about potential impacts of the nuclear fuel cycle is readily available from a multitude of easily obtainable standard references for those who wish to pursue the subject further (see Sec. 2).

3.1 Potential Radiological Health Impacts of the Coal Fuel Cycle

Although knowledgeable scientists have long been aware that the coal fuel cycle releases significant amounts of naturally occurring radioactivity to the environment, relatively few studies have been done to assess the potential impact of the entire coal fuel cycle. Those that have been published have dealt primarily with the potential impacts of coal combustion.[51,65-70] Some of these studies

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neglect food pathways, while none have completely considered the potential impact of atmospheric Rn-222 emissions, leaching of Ra-226 and other long-lived radionuclides from coal-cleaning wastes and coal ash piles over long periods of time (centuries), releases of naturally occurring radioactivity from coal mines, and solubilization of toxic metals from sediments in lakes and rivers due to acid mine drainage and acid precipitation. However, the release of stable carbon dioxide depleted in C-14 from fossil fuel combustion results in a dilution of the C-14 from natural and man-made radiocarbon in the world's atmosphere. The dilution, called the Suess Effect, then results in a reduction in the population dose from C-14. It has been claimed that these reductions result in a negative radiological impact for the coal fuel cycle.[67] These and other considerations are discussed below.

3.1.1 Radiological Effluents and Potential Health Impacts of Radioactivity From Combustion of Coal

Although two United Kingdom (U.K.) reports[52,70] are very recent and carefully done, they may not be representative of the impact of coal-fired power plants in the United States because of the much smaller land area and higher population densities near U.K. facilities as compared with those near modern coal-fired plants in the United States. As a result, a 1979 Environmental Protection Agency (EPA) report[51] was used for this assessment. The EPA release estimates, normalized to a GW(e)-yr, are shown in Table 15. The atmospheric dispersion models are similar to those used for radioactive releases from the nuclear fuel cycle and will not be discussed. For a new station composed of two late-model coal-fired power plants (meeting EPA clean air standards), EPA estimated a range of 0.0067 to 0.29 fatal cancer per GW(e)-yr among the total population within 80 km (50 miles) of the model station over a period of 100 years for rural and urban sites. This range would characterize most of these facilities in the United States. Population doses beyond 80 km were not addressed, but would increase the risks in varying degrees, depending on whether the site was urban or rural. The range of population doses on which the EPA health impact assessments were based appears to include the U.K. estimates[52,70] discussed earlier, and those by McBride and coworkers.[50]

3.1.2 Potential Radiological Impacts Among Coal Miners

The estimate used in this report is from Reference 70, one of the U.K. reports because the author has not seen similar assessments for U.S. mines. It is uncertain how much different the doses would be in U.S. mines because much of current U.S. coal mining is from strip mines, but the U.K. estimate is 650 working-level months (WLMs) per GW(e)-yr for underground coal mining. Using the same health effects model as the one for Rn-222 exposures from the uranium fuel cycle (70 lung cancer deaths per 10^6 person-lung-rem) and assuming 6 rem per WLM (as recommended in the BEIR III report [Ref. 24]) yields 0.27 fatal lung cancer among underground coal miners per GW(e)-yr, approximately equal to the occupational risk (per GW(e)-yr) for the entire nuclear fuel cycle. One would expect a smaller value for strip-mined coal because much of the radon would be dispersed during the strip-mining process.

3.1.3 Potential Long-Term Radiological Impacts of Coal Ash Piles

A critical flaw exists in all the current evaluations of the potential long-term radiological impacts of coal combustion reviewed by the author. Those

Table 15 Atmospheric emissions of radionuclides from EPA model of a new coal-fired station (2 units) per GW(e)-yr*

Radionuclide	Emissions (Ci/GW(e)-yr)
Uranium Series	
Uranium-238	4.2E-2
Thorium-234	2.1E-2
Uranium-234	4.2E-2
Thorium-230	2.1E-2
Radium-226	3.2E-2
Radon-222	2.7
Polonium-218	2 1E-2
Lead-214	4.2E-2
Bismuth-214	2.1E-2
Polonium-214	2.1E-2
Lead-210	1.1E-1
Bismuth-210	2.1E-2
Polonium-210	1.1E-1
Actinium Series	
Uranium-235	2.1E-3
Thorium-231	1.0E-3
Protactinium-231	1.0E-3
Actinium-227	1.0E-3
Thorium-227	1.0E-3
Radium-223	1.4E-3
Radon-219	1.2E-1
Polonium-215	1.0E-3
Lead-211	1.0E-3
Bismuth-211	1.0E-3
Thallium-207	1.0E-3
Thorium Series	
Thorium-232	1.8E-2
Radium-228	2.8E-2
Actinium-228	1.8E-2
Thorium-228	1.8E-2
Radium-224	2.8E-2
Radon-220	2.2
Polonium-216	1.8E-2
Lead-212	1.8E-2
Bismuth-212	1.8E-2
Polonium-212	1.8E-2
Thallium-208	1.8E-2

*These emission rates do not include contributions from any radionuclides in scrubber reactants or coal ash wastes. Multiplied by 1.4 to convert to GW(e)-yr basis (see Ref. 51, Table 4.4-8).

few studies (for example, Ref. 69) that mentioned the possibility of leaching uranium, thorium, radium, and other heavy radioactive elements from coal ash have failed to evaluate the potential leaching of heavy metals from coal ash piles over periods of tens or hundreds of years or longer, as well as the potential concurrent increase in Rn-222 emissions from the ash piles over those periods.

Final decisions on the fate of coal ash produced in the future have not yet been made, making an assessment of this impact very uncertain. If flue gas desulfurization (FGD) sludges are neutralized and stabilized before being dumped with the ash, the likelihood of acid leaching of heavy metals from the vitrified ash will be reduced. However, the present practice is to dump the acidic FGD sludges with coal ash usually near or at the power plant because the disposal costs for 0.3 million to 0.5 million tons of these wastes per GW(e)-yr are already quite high. The measurements of actual Rn-222 emissions from ash by Beck and others[69] (for example, using recently vitrified ash in distilled water) may not be relevant to long-term impacts because freshly vitrified material (a few years old or less) has not been subjected to enough weathering to provide a realistic estimate of the potential releases of Rn-222 as well as Ra-226 over decades or centuries. This fact is particularly true if acidic FGD sludges are also mixed with the ash. For example, if the acidic sludges were to leach half of the Ra-226 from the ash in 100 years, the radon-222 emanation rate per curie of Ra-226 from the leached ash would be comparable to that from Ra-226 in some uranium mill tailings because present-day reclamation of coal ash (that is, a foot or so of dirt cover) would not greatly reduce the Rn-222 emanation rate. The estimated Ra-226 in the pile would be about 2.7 Ci per GW(e)-yr.[51] For the subsequent 100 years, it would be reasonable to assume that the amount of Ra-226 leached into the interstitial pore space would gradually increase until a large fraction became available for migration with ground water. Assuming that 50% of the Ra-226 in the coal ash is leached during 100 years, the Rn-222 emanation rate from an ash pile (with depths comparable to those of unreclaimed uranium mill tailings) could be about 10 Ci per year per GW(e)-yr. This rate can be compared with about 1 Ci per year per GW(e)-yr during the 100-year period following reclamation of mill tailings required to meet current NRC standards for newly licensed uranium mills.[71] The radiological risk from Rn-222 releases during the 100-year period following production of 1 GW(e)-yr by coal combustion, using the same models as for uranium tailings, would be about 0.005 cancer death. Cancer risks would probably be higher for coal-fired plants located near large urban populations in the East (as opposed to those located in the Far West), and higher still for coal-fired stations using coal or lignite with higher-than-average concentrations of the uranium, actinium, and thorium series. The public health impacts from Rn-222 releases from coal ash waste conceivably could approach or exceed those from normal operation of the nuclear fuel cycle, particularly if present practices are not drastically altered.

Similarly, the leaching of Ra-226 from the coal fuel cycle to surface waters could result in radiological impact comparable to that of Ra-226 releases to surface waters from the nuclear fuel cycle. The release of only about 0.13% of the Ra-226 present in coal ash piles per GW(e)-yr to the same river system assumed for the nuclear fuel cycle would result in the same public health risk (0.038 latent cancer death and 0.026 genetic effect) as that from Ra-226 released from the nuclear fuel cycle (UF_6 conversion plant) per GW(e)-yr. Release of a few percent or more of the Ra-226 in the coal ash pile could be comparable to the potential public health risk per GW(e)-yr from the entire nuclear fuel cycle including current estimated risks of catastrophic nuclear accidents. However, on the average, the Rn-222 risks should be less, particularly if disposal methods for coal ash wastes are modified by stabilization of FGD sludges and reclamation practices are improved (for example, by use of clay caps or other less permeable cover). Although all these risks are small, considerable thought and care should be given coal-ash and FGD-sludge disposal to minimize leaching of Ra-226 and the other 34 radionuclides also present in the ash (see Table 15) to public water supplies.

3.1.4 Potential Long-Term Radiological Impacts of Coal Cleaning, Acid Mine Drainage, and Acid Rain

As shown in the preceding section, only a small quantity of Ra-226 released to surface waters can cause a radiological impact on the public comparable to that of the entire nuclear fuel cycle. However, because the content of Ra-226 (and other natural nuclides) in coal is comparable to that in natural soil, it is unlikely that the impact of these releases from coal cleaning, acid mine drainage, or acid rain will be large per GW(e)-yr. Unfortunately, the combined increases in pH in surface waters from acid mine drainage and acid rain from the region's mining and power generation may be different from the sum of the individual contributions to acidity per GW(e)-yr because the solubility of heavy metals may not increase in direct relation to acidity due to the presence of other solutes. As a result, to attempt to quantify generically the impacts of coal cleaning, acid mine drainage, or acid precipitation on increased availability of heavy metals in drinking water is not feasible. All that can be said is that increased acidity will usually increase concentrations of heavy metals (including Ra-226) in surface waters, and that population dose commitments and risks should also increase over time.

3.1.5 The Suess Effect

As mentioned in Section 3.1, the release of stable carbon (as carbon dioxide) that is depleted in natural C-14 results in a reduction in the population dose from C-14 (both natural and man made) in the biosphere. The Environmental Protection Agency found about a 500-person-rem reduction in world population dose over 100 years per GW(e)-yr from the Suess Effect.[67] The British estimated a 2,200-person-rem effective dose equivalent reduction over a period of 500 years for coal burned in the United Kingdom, including both first-pass and subsequent doses to the world population.[52] A dose of 500 person-rem to a constant world population of about 10 billion persons results in an average dose of about 5×10^{-5} mrem per person (essentially over a lifetime). Thus, the dose reduction to a constant U.S. population of 300 million would be about 15 person-rem for a 100-year collective dose equivalent commitment. This corresponds to a reduction of about 0.0018 latent cancer death in the United States during the next century. Thus, although the reduction in cancer risk to the world population may be comparable to the cancer risk from coal combustion to people living within 80 km (50 miles) of a modern coal-fired plant (0.0067-0.29 [see Ref. 51]), the cancer risk to the U.S. population from coal combustion is not significantly reduced by the Suess Effect.

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3.2 Potential Nonradiological Health Impacts of the Coal Fuel Cycle

The nonradiological health impacts of the coal fuel cycle are now a subject of intense debate--much more so than those of the potential risks associated with exposure to low-level ionizing radiation. The impacts range from relatively small risks, such as an increase in asthma suffering, to macroscale impacts on the world, such as those that would result from an uncontrolled Greenhouse Effect. Considerable controversy surrounds the current health effects models used to estimate the impacts of sulfur emission from coal-fired power plants, particularly when these models are used as the basis for regulating sulfur releases.

These and other problems are discussed in the sections that follow.

3.2.1 Potential Health Impacts of Coal Mining

Health impacts of coal mining occur predominantly among the miners, result from chronic exposure to coal dust, and include acute mortality from many types of accidents. Chronic inhalation of coal dust (primarily in underground mines) results in coal workers' pneumoconiosis (CWP), or black lung disease. (See Refs. 72-74 for more detailed information about CWP.) Since the passage of the Federal Coal Mine Health and Safety Act of 1969 (PL 91-173), working conditions in underground mines have gradually improved. As a result, the prevalence of CWP and accidental deaths and injuries is declining. In addition, the percentage of coal mined by surface methods has continued to increase and now accounts for 50 to 60% of total coal production.

Both CWP and accident and injury rates are much lower in surface mines. Commonly cited estimates of accident fatality rates for a 1,000-MWe plant operating continuously for 1 year (that is, a GW(e)-yr) are 0.54 for underground mines and 0.09 for surface mines; however, these rates appear questionable.[72] Earlier estimates of the Council on Environmental Quality (CEQ) are considerably higher (1.67 and 0.308, respectively).[64] The latter were employed by the National Academy of Sciences for its 1979 estimates,[4] and will be used for this assessment. These equate to 2.2 and 0.41 deaths per GW(e)-yr. Since surface mining now produces half the coal in the United States, the average would be 1.3 deaths per GW(e)-yr. The CONAES report failed to estimate risks of injury and disease among coal miners.

Because the CONAES report apparently accepts the 1973 CEQ estimates,[64] the CEQ accidental injuries values were also used for this assessment. Assuming that the present production methods prevail (that is, about half the coal mined will come from surface mines), the injury rate would be about 66 per GW(e)-yr in the United States. CONAES also failed to quantify the risks of CWP and progressive massive fibrosis (PMF), stating only that if current dust standards are maintained, the incidence of CWP should be less than 3%, and of PMF less than 0.25%. Reference 72 indicates that in 1973 (after these dust standards were achieved), productivity of miners was about 10.2 metric tons per miner-day. By assuming that it takes 2.5 million metric tons to produce a GW(e)-yr and half that fuel comes from underground mines, one can calculate about 0.3 case of CWP and 0.03 case of PMF. Such small numbers do not significantly increase the overall risk of disease or injury among coal miners.

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With increased coal utilization, an influx of inexperienced miners into coal mines is anticipated. Because historical data show that inexperienced miners tend to have higher mortality and injury rates, it is possible that risks of coal mine accidents may increase in the years ahead in spite of better regulated mines.[75]

A potential long-term health impact of underground coal mining may result from acid mine drainage into surface waters eventually used for human and agricultural purposes. This risk, while unquantifiable now, could be significant over a long period of time as increased acidity gradually leaches toxic and carcinogenic trace metals from bottom sediments into water supplies. These materials, including cadmium, nickel, mercury, the uranium and thorium series, and others, could be ingested directly or through food pathways (for example, finfish, shellfish, irrigated crops, meat, and milk).

3.2.2 Potential Health Impacts of Coal Beneficiation

After being mined, coal must first be cleaned (beneficiation) to remove impurities before shipment. The fluid most commonly used for cleaning is water, which also removes mineral sulfur (for example, pyrite). As a result, the wash water becomes acidified before it is returned to surface waters. This acidity not only dissolves heavy toxic trace metals from the waste, it can also act to remove similar metals from sediments as does acid mine drainage. Studies to date demonstrate that significant amounts of trace metals leach from coal processing wastes. Although the amount (approximately 30% of the total) is much less than that resulting from acid mine drainage, coal preparation wastes are still accumulating, while acid mine drainage is gradually being reduced. As a result, concentrations of certain metals, such as cadmium, may exceed U.S. Public Health Service standards in some water basins because of combined drainage from mines, solid waste (gob) piles, and coal refuse banks.[76]

After physical cleaning of coal, the solid waste is usually dumped nearby to form spoil (culm) banks or waste piles. These piles are subject to slope failures and landslides, and, because of their coal content, are subject to spontaneous fires. Runoff from gob piles is an additional source of acid drainage, and gob fires in 250 million tons of burning waste in the United States are believed to contribute about 5% of the overall national burden of carbon monoxide.[72] As carbon monoxide emissions from automobiles continue to decline, this percentage may increase. In addition, the sulfur emissions are also substantial. Unfortunately, none of the potential impacts have been reliably quantified. New coal-preparation plants are now required to meet EPA New Source Performance Standards by using the best available control technology. If this practice continues, effluents associated with new facilities will be much lower than in past years and are not expected to result in a substantial increase in public health impacts.

The CONAES report estimates about 0.027 accidental death among workers per GW(e)-yr, and this value is used in this assessment.[4]

The CONAES report failed to estimate risks of injury and disease among coal-processing workers. Because the CONAES report apparently accepted the 1973

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estimates of CEQ,[64] these accidental injury values were also used for this assessment. If the present cleaning methods prevail, the injury rate will be about 3.4 per GW(e)-yr.

3.2.3 Health Impacts of Coal Transportation

A 1,000-MWe coal-fired power plant will consume between 2.1 million and 3.4 million tons of coal per year, depending on the Btu content of the coal and the plant-operating conditions.[72] With the exception of mine-mouth power plants, moving such large quantities of coal from the mine to the power plant requires combinations of trucks, trains, barges, and pipelines. At the present time, most coal is transported by truck from mines (particularly strip mines) to central shipping areas, where about half of all utility coal is then shipped by rail. Typically, 1,000-MWe plants require about one unit train per day (one hundred 100-ton cars and five diesel locomotives). The average haul distance is gradually increasing (290 miles [464 km] in 1973, 500 to 700 miles [800 to 1,120 km] during the 1980s) as a result of shipment of coal to areas that have not, in the past, used much coal for power generation (for example, New England and the Pacific Coast).[72]

According to a recent study, coal trains are the cause of an average of 0.79 death and 8.8 injuries per million tons of coal hauled.[72] Thus, a coal-fired power plant can be expected to be the cause of about 2.2 to 3.6 deaths and about 25 to 40 injuries per GW(e)-yr. Most of these deaths would occur at grade crossings in collisions between unit coal trains and automobiles. If the projected increase in hauling distances occurs, these numbers could increase by about 160 to 230%. On the other hand, mine-mouth plants would have much lower risks. These estimates of mortality and injury are comparable to the 1973 CEQ estimates of deaths and injury (3.1 deaths and 31 injuries per GW(e)-yr)[64] that were accepted by the NAS (CONAES) in 1979.[4] About half of the deaths would occur among the general public according to NAS.

3.2.4 Potential Nonradiological Health Impacts of Coal Combustion in Power Generation

Coal-fired power plants release large quantities of a very complex mixture of gases, vapors, and particulates to the atmosphere. Although laboratory studies that measure a range of endpoints from acute exposure to individual pollutants have been carried out, it is possible that synergistic effects from chronic exposure to complex mixtures downwind from a coal-fired plant result in much different effects than the acute effects measurements would indicate. The problems are similar to those facing radiation biologists estimating the effects of low-level ionizing radiation. Are the dose response curves linear to low doses? Do thresholds for individual components of the mixture exist? Are there synergistic effects similar to those in the situation of exposure to asbestos and cigarette smoking? No one knows, and it is doubtful if a level of understanding comparable to that relating to radiation exposure will be reached for many more years.

The emissions from a coal-fired plant depend to a great extent on the type and geochemistry of the coal burned, and on the type of burner and operating conditions at the plant. As the Btu content of the coal declines, more coal must be burned to produce the same amount of electricity. An increase in ash content and a decrease in Btu content result in even greater particulate emissions for a given particulate removal system. Particulate emissions include over 30 naturally occurring radionuclides in the uranium, thorium, and actinium series (see Ref. 51 and Table 15) and over 50 stable elements, several of which are known carcinogens or toxic to living things.* Furthermore, the content of these various elements differs markedly for coal from different geographic regions.[72]

The particulate-removal efficiencies (99% or more) required for new coal-fired plants are based on mass collection and do not reflect efficiencies for removing respirable-size particulates (older plants generally have little or no particulate removal). Electrostatic precipitators, for example, typically have overall operating efficiencies in the range of about 80 to 90% for removing respirable particulates (less than a few micrometers).[72] Because deposition of the particulates in human lungs is a requirement for causing an effect, the health risks from particulate emissions are much greater than those the mass-removal efficiency of precipitators (or other devices such as cyclone separators) would indicate at first glance. Furthermore, the concentrations of toxic trace elements appear to increase with decreasing particle size; thus, the health risks become even greater.[77] Finally, the smaller the particulate size; the greater the distance the particulates can be carried by prevailing winds (they can be carried from low-population zones to urban areas where many more people would be exposed to them). During transport, the same trace metals assist in catalyzing the conversion of sulfur dioxide to sulfate (believed by some to be the major contributor to respiratory disease and death, as well as acid rain from coal-fired power plants).[75,78-81]

In addition, the hydrocarbon content of coal is an incredibly complex and highly variable mixture of organic species, several of which are also known carcinogens.[76,78] The relative ignorance of the risks associated with exposure to these complex mixtures is analogous to the relationship between cigarette smoking and lung cancer. Cigarettes have been analyzed by every known procedure during the last decade, and several carcinogens have been identified. No one has conclusively demonstrated which of these carcinogens are the primary causes of lung cancer among smokers, yet few informed scientists doubt that the mixture, when inhaled, causes lung cancer. In the case of emissions of several known carcinogens (at high concentrations) from coal-fired plants, however, it remains yet to be shown that chronic public exposure at low concentrations is associated with a definite cancer risk, even though respirable coal fly ash is definitely mutagenic.[82] Because the same uncertainty is true for chronic, low-level radiation exposures from nuclear power plants, it would seem prudent to use a linear-dose-response assumption for each of the known carcinogens (at high doses) similar to that assumed for exposure to radiation. Unfortunately, so little is known, even at high doses, about the dose response of many chemical carcinogens contained in coal that these calculations cannot be made yet with a high degree of reliability. A partial list of chemical carcinogens from coal combustion includes arsenic, cadmium, chromium, iron oxide, nickel, and benzo-a-pyrene (plus other similar aromatic hydrocarbons).[78]

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*Scrotal cancer (from coal soot) in children who were chimney sweeps was the first cancer shown to be caused solely by occupation. This relationship was discovered in England in 1775 by Sir Percival Potts.

In the case of exposure to noncarcinogenic chemical species, it is now hypothesized that chronic exposure to low levels of pollution (accompanied by cigarette smoke and so forth) results in gradual irreversible damage to cardiovascular functions over a lifetime, which, in turn, causes death in chronic sufferers when a severe air pollution episode occurs.* Many of these deaths occur among the elderly and severely ill during episodes such as those documented in London (1952),[79] Donora, Pennsylvania (1948),[80] and New York (1963-68).[81] These observations, plus increased asthma attacks and other episodes among children who have a higher sensitivity to air pollution, lend support to such a hypothesis, but cannot prove it in the presence of other critically important but unmonitored agents, such as exposure to cigarette smoke, in the urban environment. It should be noted that the classic studies by Winklestein and coworkers[83] and Lave and Seskin[84] are still the most quoted. Lave and Seskin provide a vigorous defense of their models and results, claiming that suspended particulates, sulfur dioxide, and sulfate account for most of the variance in mortality using multiple regression analysis, and that considerable internal consistency and reproducibility exist.[85,86] Recent studies by others also conclude the relationships exist, and provide estimates of effects (mortality and morbidity) that range from zero to the hundreds, depending on the sulfur and Btu content of the coal, the nearness of the plant to population centers, and other factors.[87,88]

Nevertheless, the recent National Academy of Sciences (CONAES) report, concluded:

> The health impact of air pollution from coal combustion products is inconclusive. The widely quoted studies indicating severe impact of sulfates resulting from atmospheric transformation of sulfur dioxide emissions are seriously flawed. On the other hand there is also no evidence to suggest conclusively that present standards are too tight, or even that there are no risks at present ambient levels.
>
> The factor of time must be emphasized....Experience has shown that important aspects of the epidemiolgical studies...cannot be hurried to meet the demands of policy,...chronic and late effects take time to develop.[4]

Moreover, the National Academy of Sciences CONAES[4] rejected the initial findings of its Risk and Impact Panel on the health effects of coal combustion.** The draft report of the Risk and Impact Panel indicated a range from near zero to several hundred deaths among the population within 80 km (50 miles) of the plant per GW(e)-yr, depending on the method of analysis. However, the caveats were so constraining that they leave the reader in the difficult position of deciding whether the range of numerical mortality estimates, based on assumed emissions of sulfur oxides and particulates (as an index of total pollution), are a reasonable reflection of the true uncertainties and their causal factors. The present circumstances are believed analogous to other controversies that have plagued decisionmakers in recent years. These include such problems as assessing the risk of cigarette smoking, use of saccharin, and low-level radiation exposure. Such uncertainties generally arise because of an inability to prove cause and effects relationships, particularly from very low-level exposures whose effects (if any) are within the normal range of naturally occurring mortality and morbidity.

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*See for example: A. J. Dvorak et al; "The Environmental Effects of Using Coal for Generating Electricity," USNRC Report NUREG-0252, p.144, June 1977.

**National Research Council, National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems, Risk and Impact Panel, "Risks and Impacts of Alternative Energy Systems," Washington, D. C. (unpublished draft)

As a regulatory agency, the NRC must make licensing and regulatory decisions based on the best information available. That is also true when comparing the risks of viable alternative energy cycles. Because the human health impacts of coal combustion are potentially greater than the impacts from nuclear energy, the author believes that it is helpful to provide decisionmakers with a reasonable range of estimated risks, even in the absence of a clear scientific-community consensus.

In this regard, the detailed investigative work and statistical analyses of Lave and Seskin[85,86] are a useful starting point for providing a range of estimated risks of air pollution from coal combustion which is a major source of air pollution in the United States. It is believed that statistical correlation methods such as those used by Lave and Seskin are, by themselves, not yet adequate to provide an accurate estimate of potential health risk.* However, in conjunction with other toxicological and epidemiological studies,[77,79-89] they provide a useful basis for estimating the order of magnitude of such risks.

Subsequent to publication of the CONAES report, investigators at Brookhaven National Laboratory have made more sophisticated analyses of the available epidemiological data, using the works of Lave and Seskin and others as a starting point. Hamilton estimated about 0.9 death within 50 miles and 9.2 deaths among the total U.S. general public per GW(e)-yr from air pollution associated with operation of a modern coal-fired power plant.[88] As with the case for ionizing radiation, the possibility of zero risk from low-level exposure could not be excluded by the data. A similar conclusion was reached by Morris after additional studies.** Morris concluded that depending on the presence or absence of an effects threshold for sulfur oxides, the potential mortality per GW(e)-yr could range from 0 to 60 for the total United States from a plant situated in the Ohio Valley (median of 21 deaths with a 90% confidence interval). Assuming an effects threshold of 10 $\mu g/m^3$ for sulfates reduces the upper range to 30 (median of 10), with a more probable value of about 5 deaths per GW(e)-yr among the total U.S. population. In light of these more recent, although still cautious estimates, it was assumed that the potential impacts of modern conventional coal-fired power plants using state-of-technology flue gas desulfurization range from 0 to 60, while more probable risks are in the range of about 5 to 10 deaths per GW(e)-yr.

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*These studies were the basis for the estimates of 4 to 140 deaths per GW(e)-yr reported in the 1977 draft of this report.

**S. C. Morris, "Health Risks of Coal Energy Technology, in Health Risks Associated With Energy Technologies (Westview Press, Boulder, Colorado, 1983).

Although neither of these more recent studies provided estimates of disease or injury rates per GW(e)-yr, clearly those effects, ranging from simple irritation of the eyes, nose, throat, and lungs to serious respiratory insufficiency and cardiovascular stress, must greatly exceed the mortality rates resulting from those impacts. For the purposes of this report it was assumed that the morbidity risks are at least 10 times greater than the mortality risks.

Quite obviously, substantial uncertainty also exists (as it does for the health risks of the nuclear fuel cycle) over future technological developments that would improve the cost-effectiveness of air pollution control systems. This is also the case for future regulatory requirements which may change the health effects estimates for the coal fuel cycle. No attempt has been made to assess such uncertainties.

The CONAES report estimated that the occupational accident mortality risk at coal-fired stations is about 0.013 death per GW(e)-yr;[4] this value was used for this report.

3.2.5 Potential Nonradiological Health Impacts of Coal Ash Waste

As in the case of potential long-term impacts of radioactive leachates from coal ash piles, no one has quantified the potential long-term impacts of the nonradioactive materials from coal ash piles. Measurements of trace metals in fly ash and bottom ash transport water (water used to sluice ash to an onsite ash pond) definitely show that many of the metals can be readily leached from the vitrified ash in acid solutions, and some leaching occurs even in distilled water.[72,76,89] It should also be noted that stable toxic and carcinogenic elements can literally remain hazardous forever because they do not disappear by radioactive decay. Most of these leachates (like many very long-lived radionuclides) will almost certainly end up in sediments, where they will eventually become part of the lithospere, and thus be out of the food pathways for humans. In the relatively short term (decades or centuries), some of these materials could have a significant effect on populations not only from uptake through food chains and drinking water but by removing certain surface waters from the total reservoir of potable water. Consider, for example, that about 20 to 30 tons of cadmium are disposed of in the ash pile of a coal-fired power plant per GW(e)-yr. The ash concentration of cadmium is an order of magnitude (or more) higher than the average for the earth's crust or shale.[90] If the cadmium content of surface or underground water is proportional to the cadmium present in the soil the water flows over or through, leaching of this metal from large numbers of ash piles when added to that from other sources could raise cadmium concentrations high enough in certain domestic water sources to preclude safe human consumption. Unless care is taken in disposing of coal ash (for example, by use of clay caps and liners and stabilization of FGD sludge), leaching of cadmium and other toxic or carcinogenic metals (for example, nickel, chromium, arsenic, lead, and selenium) could become a long-term, chronic exposure problem of unknown magnitude.

3.2.6 Health Risks Associated With Subsidence and Fires in Underground Coal Mines

The general public is only now becoming aware of the results of the poor control of underground coal mining during the first part of the century and lacks an appreciation of the possibilities of underground coal mine subsidence and fires. Many areas in Appalachia are now seeing a rise in subsidence, often accompanied by uncontrolled underground fires, as the normal slow process of settling in mined-out areas occurs.[91]* Nevertheless, the health risks appear small relative to other aspects of the coal fuel cycle and, therefore, will not be discussed further.

3.2.7 Perspectives on Nonradiological Risk

As in the case of the assessment of the nuclear fuel cycle, it lends perspective to compare these estimates with other more commonplace, familiar risks. Again, the comparisons are not intended to be all inclusive, and other comparisons are possible. The health risks for the coal fuel cycle are, unfortunately, somewhat obscured by the inability to estimate some of the potential health impacts. By using the data from Table 16, and conservatively reducing the 8.8-15 range of risks of mortality to 5 deaths per GW(e)-yr, a reasonable estimate of the lower-bound risks of the coal fuel cycle can at least be provided. The uncertainty associated with the lower-bound risks for the majority of coal-fired plants is fairly small because nearly half the risk comes from coal transportation for which the statistics are fairly stable. The uncertainty associated with upper-bound risks is almost certainly one or more orders of magnitude since many of the potential unquantified risks are large, and cannot be reasonably estimated because final decisions regarding such items as regulation of coal ash and mining wastes have not yet been made.

Five deaths per GW(e)-yr is about five times the total risk from the nuclear fuel cycle per GW(e)-yr. This level of risk can be compared directly with those shown in Table 11 in the preceding section where risks of the nuclear fuel cycle are discussed. From Table 11, it is clear that the lower-bound risks for the coal fuel cycle are much less than those from automobile driving, falls, fires, or drowning, and represent possibly about a 0.05% increase in the risk of mortality from all other causes if all the electricity in the United States were generated by coal-fired power plants.

3.3 Other Potential Impacts of the Coal Fuel Cycle

3.3.1 The Greenhouse Effect and the Relationship to Coal Combustion

It has been known for decades that combustion of fossil fuel releases carbon dioxide to the atmosphere. It has also been known that carbon dioxide is transparent to almost all incoming light from the sun, but strongly absorbs certain

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*Reference 91 noted that only 2 million of the more than 9 million acres of land surface over mines has subsided, and 2 million more could subside by the year 2000.

Table 16 Summary of potential health effects among the total U.S. population per GW(e)-yr for the coal fuel cycle*

	Potential accidental deaths		Potential radiogenic cancer mortality		Potential accidental injuries and disease		Potential nonradiogenic disease mortality		Totals	
Source of risk	Occupational	General public	Occupational	General public	Occupational	General public	Occupational	General public	Deaths	Injuries and disease
Coal mining	1.3	~ 0	0.27	> 0	66	> 0	> 0	> 0	~ 1.6	~ 66
Coal processing	0.027	> 0	> 0	> 0	3.4	> 0	> 0	> 0	~ 0.027	~ 3.4
Transportation	1.1	1.1	~ 0	~ 0	15	16	~ 0	~ 0	~ 2.2	~ 31
Power generation	0.013	~ 0	> 0	0.007-0.3	1.8	50-100**	> 0	5-10	5-10**	50-100**
Waste management	> 0	> 0	> 0	0-1	> 0	> 0	~ 0	> 0	> 0-1	> 0
Totals	~ 2.4	~ 1.1	~ 0.27	~ 0.007-1.3	~ 91	66-120	> 0	5-10	8.8-15	150-200

*The ranges presented in this table are the range of best-estimate values in the literature, and do not reflect the total range of values in the literature.

**These ranges are currently controversial; the actual range could be from 0 to perhaps several hundred (see Section 3.2.4 for details).

infrared heat radiation radiated from the surface of the earth back into space. The principle is called the Greenhouse Effect.

Although a small constituent of the atmosphere (330 ppm by volume in 1979),[4,28] carbon dioxide is a factor in the control of atmospheric temperature. The contribution of fossil fuel combustion to the observed gain is uncertain, but apparently it is major[4,28,29] (currently, about 20 billion tons per year from fossil fuels). Since 1950, the release rate of carbon dioxide to the atmosphere has been increasing about 4.3% per year: at this constant rate, the carbon dioxide concentration could double during the next century. At an increasing rate per year, doubling could occur within about 50 years.[30] Doubling of the carbon dioxide concentration of the atmosphere would lead to an estimated 10 K (18°F) increase in temperature over the Antarctic. This could cause melting of the West Antarctic ice sheet over a period of decades, thus raising the average ocean depths by about 5 m (about 16 ft).[30] Such an increase, which could occur within the lifetimes of many people now living, would be economically, environmentally, and socially catastrophic (for example, many major sea ports and coastal areas would be flooded). (See Ref. 31 for a detailed example of potential flooding in the Nation's capital, located about 90 miles inland from the Chesapeake Bay.) Although the uncertainties remain large, the potential short-term consequences are so great as to require serious consideration. Unfortunately, some experts warn that by the time such melting could be confirmed, it may be impossible to prevent further melting even if all man-made sources of carbon dioxide were to cease. That is because it takes a long time for the oceans (the ultimate carbon dioxide sink) to remove the excess carbon dioxide from the environment. Thus, it appears likely that once the melting process has been identified, it may be irreversible.[28-30] Large-scale melting of the ice caps would result in much greater increases in ocean depths (several hundred feet), but would occur very slowly over a period of centuries, allowing time for mankind to gradually accommodate to the changes.[4,28] Nevertheless, such a rise in sea levels would inundate large coastal land areas and ports causing serious economic penalties and social disruption.

In addition, such global temperature increases could lead to changes in regional rainfall and crop production.[4,28,29] In the United States, an increased global temperature could lead to an increase in desert lands and a decrease in grain production. Because surplus U.S. grains literally keep millions of people above the cutting edge of starvation, any decreases in U.S. grain production could have fairly immediate and devastating effects on them.

Although these changes might eventually be offset by greater crop production in higher latitudes[29] (for example, Canada, Greenland, Siberia, and Alaska), the impact on many nations would be immense, and could be catastrophic without unprecedented international cooperation.

3.3.2 Potential Impacts of the Coal Fuel Cycle on Ecosystems

The 1979 NAS CONAES report concluded that coal is one of the most ecologically disruptive energy sources available to man.[4] The CONAES report also noted, "Threats to ecosystems are generally speculative and subject to a high degree of uncertainty." Most of the processes such as acid mine drainage, acid rain, and leaching of toxic (or radioactive) trace metals to surface and underground water, which could also lead to impacts on numerous ecosystems, are discussed in some detail in Sections 3.1 and 3.2. Some potential ecological impacts (subsidence, Greenhouse Effect, and increases in concentrations of toxic metals in surface waters) have also already been mentioned. In this section, potential ecological impacts are briefly presented although no attempt is made to evaluate these risks to the quality of man's environment, because at present no way of quantifying these impacts is known.

CONAES identified the following major concerns:

(1) Without proper management, underground mining can affect underground water systems and their drainage patterns and cause land subsidence.

(2) Strip mining, without proper reclamation, is ruinous to the surface land. In some areas, lasting reclamation is doubtful especially where water requirements are high and water supply is low (for example, the Western States).

(3) Sulfur dioxides and acid precipitation from uncontrolled coal combustion can damage forests, agriculture, and fisheries, and through leaching processes, increase the ground and surface water concentrations of toxic trace metals.

(4) Carbon dioxide emissions from coal combustion could lead to (a) drastic alterations of both natural and agricultural ecosystems possibly within 50 years as a result of extensive and complex changes in precipitation patterns, and (b) a slow melting of polar ice leading to slowly rising sea levels (and declining salinity) and changing coastlines (affecting fragile wetlands).

Reference 72 (Tables A-C) represents an NRC-funded attempt to develop a generic table of environmental impacts and effects analogous to that presented in Section 2.2.2 for the nuclear fuel cycle. Table 17 shows a summary of some of these considerations. In general, with the possible exception of carbon dioxide

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releases, the ecological impacts of these releases should be acceptable for the coal fuel cycle as long as new mines and power stations meet the air and water quality standards that are being established by EPA. Thermal impacts should remain insignificant for properly designed, sited, and operated coal power stations.

Table 17 Summary of other environmental considerations for the coal fuel cycle per GW(e)-yr

Natural resource use	Range for proposed current standards
Land (acres)	
Disturbed (assuming 50% from strip mines)	310-330
Committed	19-33
Water (millions of gallons)	8,600-11,000
Plant effluents to atmosphere (metric tons)	
Sulfur oxides	21,000-43,000
Nitrogen oxides	21,000-24,000
Carbon monoxide	1,400
Particulates	1,100-3,600
Fluorine	0.11-0.36
Lead	0.11-0.38
Mercury	0.04-0.14
Nickel	1.1-3.6
Selenium	0.066-0.22
Thallium	0.033-0.11
Antimony	0.036-0.59
Arsenic	0.31-2.1
Beryllium	0.005-0.014
Cadmium	0.006-0.021
Copper	0.43-1.4
Plant effluents to water bodies (sulfates, etc.)	(unspecified but potentially large)
Thermal	(unspecified)

Note: See Table 13 for conversion factors.

Source: Reference 72.

3.3.3 Potential Materials Damage From Combustion of Coal in Power Generation

This area was neglected by the 1979 CONAES report.[4] Any such estimates are uncertain, but perhaps less so than those dealing with health effects or ecological damage, because they deal with relatively simple impacts (such as oxidation of paints and corrosion of materials) that can be measured in the laboratory.

One report summarized the monetary cost of damage from air pollution (all sources) in the United States as follows:[92]

Type of damage	Consumer cost and year of estimate
Electrical contacts (SO_2 and H_2S)	$ 64 million (1970)
Rubber products (ozone)	$ 470 million (1970)
Dye fading (ozone)	$ 206 million (1970)
Corrosion of metals (all pollutants)	$1,450 million (1971)
Exterior paints (all pollutants)	$ 704 million (not given)

A second study, which deals more directly with coal combustion, concluded that the cost of material damage was approximately $4.8 million to $5.3 million per year of operation for a modern, large, coal-fired plant sited in an urban area.[93] The cost declined (1) when the plant was located in a remote area or (2) if the sulfur emissions were reduced.

3.3.4 Potential Health Costs From Combustion of Coal in Power Generation

An area closely related to materials damage is health damage from air pollution. Reference 93 estimated that health costs (medical expenses, absenteeism, and so forth) as a result of emissions from a large, modern, coal-fired power plant would range from about $38 million per year for an urban site to about $13 million per year for a site in a remote area. Chronic respiratory disease (at $250 per case) and aggravated heart-lung disease symptoms (at $20 per case) would account for most of the costs.

One study showed that costs associated with hospital stays for persons exposed to sulfur dioxide and particulates in Allegheny County, Pennsylvania, came to about $9.8 million per year among a population of 1.6 million.[94] Both respiratory diseases and circulatory diseases suspected of being effects of these pollutants were studied. Lost work time and other social costs would add more to the total.

The relevance of these estimates to the health costs of coal combustion is highly uncertain in light of the current debate surrounding the health effects models currently available for estimating the health risks from sulfur and particulate emissions.

3.4 Summary and Conclusions

In general, the potential radiological impacts of the coal fuel cycle, like those of the nuclear fuel cycle, appear to be small in relation to other everyday risks. Although these impacts cannot be defined as well as those for the nuclear fuel cycle, it would appear that the impacts per GW(e)-yr could range between 0 and 1 cancer death in the United States during the next century, depending on many decisions (such as how coal ash will be disposed of) that are still being made and revised by Congress, the EPA, and other Federal agencies. The most realistic radiological impact of average coal utilization should be no more than 1 cancer death per GW(e)-yr, and genetic effects will be even lower. However, there is considerable uncertainty in such estimates, and actual risks in the years ahead could be quite different from those envisioned in this report. Nevertheless, it is unlikely that the radiological

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impacts over the next century will ever become as large as current estimates of other health risks in the coal fuel cycle (for example, occupational risks to miners and public risks from releases of stable toxic materials such as sulfur and nitrogen oxides, mercury, cadmium, chromium, and nickel).

The potential nonradiological health impacts contain some large uncertainties, particularly those relating to health risks from chronic exposure from power plant emissions and potential long-term health risks. As shown in Table 16, many currently unquantified risks among both workers and the general public exist. Only in the case of transportation has it been possible to provide reasonably accurate estimates of both the occupational and public risks of mortality and injury. Estimates of the occupational risks of accidental death and injuries and disease are also reasonably accurate. Collectively, these sources of risk account for about 4 deaths and over 100 accidental injuries per GW(e)-yr with perhaps about a factor of 2 uncertainty in the near future. Additional deaths, injury, and disease could exceed these values by factors of 10 or more, but the uncertainties are so large that the numerical estimates may have little real meaning.

The National Academy of Sciences (CONAES) concluded that the coal fuel cycle is one of the most ecologically damaging alternatives to the nuclear fuel cycle. Damage results from the large-scale disruption of surface ecosystems, disruption of ground water and pollution of surface waters from mining, acid mine drainage, and acid precipitation. The ecological impact of a future Greenhouse Effect could be very damaging to natural and agricultural ecosystems as well as coastal wetlands and estuaries.

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4 OTHER PERSPECTIVES ON RISK

Because the science of risk assessment is so new, parameters that are based on perceptions and social values cannot as yet be reasonably factored into quantitative assessments, such as those presented earlier in this report. However, NRC has been aware of the importance of these factors and has funded research in this area for several years.

The discussions that follow should not be construed as being a complete presentation of the subject matter nor does the sequence of sections imply merit or importance. Rather they are an attempt to present some views on issues that have not been quantified in the preceding sections. These views are not necessarily those of NRC, but will add other perspectives to the report.

The NAS CONAES report[4] cautioned risk assessors that

> No society can be free of risk, nor is the goal of a risk-free society necessarily worth striving for. (p. 577)
>
> An important question is how subjective evaluations should be taken into account along with the more objective measures, such as fatalities per GWe-plant-year of energy production. If the subjective values are ignored, energy policy may stalemate. (p. 578)
>
> A point of difference between the objective quantification of risk and its sociopolitical assessment is the role of "attitude toward risk" in the latter. An energy system may be viewed as a hazard by a particular group of people (organized or unorganized) for reasons that may not reflect biological or ecological assessments of the risks. Nuclear power, for example, may be opposed as a symbol of big government, impersonal corporate business, or unrestrained economic growth. (p. 578)

The CONAES report also noted that

> One conclusion that may be drawn is that adequate information must continually be made easily available to the public, to inform the decision-making process, and to prevent the spread of false conclusions and impressions. (p. 578)

This report is intended to contribute to that information process.

In the following sections, the questions of voluntary acceptance of risk versus involuntary exposure to it, perceived risk versus expert "objective" estimates of it, accepted versus acceptable risks, distribution of fuel cycle risks in space and time, and catastrophic versus everyday risks, and the ethical and

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moral perspectives of risk will be briefly discussed. It is hoped that such discussions will help draw the public and the experts' understanding of risk to a more common ground. More detailed information can be derived from the references cited.

4.1 Voluntary Versus Involuntary Risk

In general, people feel that risks accepted voluntarily can be much higher (and acceptable) than those that are imposed on others against their will. Laws are written to protect the public from involuntary and unwarranted risks from the acts of others. This is also one of the reasons Congress and the States have established regulatory agencies. However, decisions by such agencies for the benefit of the many almost always result in the imposition of involuntary risks on the few (see, for example, Ref. 95).

In what has now become a classic study, Starr[96] noted: "We are loathe to let others do unto us what we happily do to ourselves." He found that people "accept" voluntary risks that are up to 1,000 times greater than those they are willing to accept involuntarily but with the same approximate benefit.

Starr also pointed out that the prevalent mortality rate (about 1 chance of death per year among 100 persons) appears to be a yardstick in determining the acceptability of voluntary risk. Thus, individuals subconsciously adjust their sporting activities so that, in general, risks associated with these activities do not greatly exceed those from disease. He noted that voluntary sports tend to reach a "mature benefit-risk balance" with time--an example is the use of motor vehicles (originally a voluntary sport) which has achieved acceptance as a necessity of life for most Americans, even though about 57,000 people are killed and about 2 million suffer disabling injuries in accidents each year from this use,[62,97] and an unknown number may suffer death and disease from the byproducts (for example, asbestos fibers from brake linings, carbon monoxide, hydrocarbons, nitrogen and sulfur oxide emissions).

In reality, most individuals can seldom exercise full control over voluntary risks, and more often trade off one type of risk for another (for example, the risks of being mugged or murdered are much higher for those using public transit systems than for those driving a private auto, while the risks from transportation accidents are much lower than for private autos). Similarly, love of family, tradition, and other factors may tie individuals to small, one-industry towns, greatly limiting their ability to control their own voluntary risks.

4.2 Risk Perception

The subject of risk perception has been studied recently with increasing interest because how people perceive risks largely determines their reactions to the associated industries, technologies, or activities. If their perceptions are faulty, severely disproportionate uses of public resources to make small risks even smaller at the cost of ignoring other activities where the same resources could yield much greater benefits to society may result. One study that compared subjective perceived risks of mortality from 30 activities and technologies with expert estimates of the risks indicates that certain groups within the lay public perceive the risk of nuclear power to be as much as 100 times greater than that perceived by the experts.[98]

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It would be reassuring to believe that divergence in risk perception between various groups of people would be responsive to new information and evidence. However, Slovic noted:

> People's beliefs change slowly and are extraordinarily persistent in the face of contrary evidence. Once formed, initial impressions tend to structure the way that subsequent evidence is interpreted. New evidence appears reliable and informative if it is consistent with one's initial belief: contrary evidence is dismissed as unreliable, erroneous, or unrepresentative....Likewise, opponents of a technology may view minor mishaps as near catastrophes and dismiss the contrary opinions of experts as biased by vested interests.[98]

A recent NRC-funded study[99] concluded that technical experts must be able to describe to the public in plain language the basic tools of risk assessment, their strengths and limitations, and how the tools are used. Only then can the lay public responsibly participate in complex technological decisions.

A recent European report concluded (as have others not mentioned here) that "fear of disaster is a potent factor in the assessment of risks at individual and societal level."[100] In general, man-made disasters are far less likely to be accepted than those caused by natural phenomena. It was concluded that antipathy toward nuclear power must have a psychological basis (as opposed to a physical one) and may originate in the violent introduction of nuclear fission during World War II, from fear of the unknown, or from a range of unrecognized factors. These and other factors affect individual and societal perceptions of risk.

DuPont, a practicing psychiatrist, describes a phobia as

> Fear based on an exaggerated, unrealistic danger. For example, if you are afraid when a lion bounds out of a cage at the zoo and comes toward you, that is normal healthy fear: the danger you face is external and substantial. If on the other hand, you are afraid to go into the zoo at any time because the sight of a snake--even in a cage--strikes terror into your heart, that is a phobia....A phobia is a malignant disease of what ifs....Phobic thinking always travels down the worst possible branchings of each of the what ifs until the person is absolutely overwhelmed with the potentials for disaster.[101]

He concluded that

> When I reviewed the Media Institute's network news nuclear energy tapes,* one of the striking characteristics I saw over and over was the reporters continually going down those what if, worst case branches. That is exactly what happens with phobic people.

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*A total of 13 hours of videotapes of nuclear energy news coverage, a great deal of it related to the Three Mile Island accident.

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> The problem becomes the what if rather than what is....I am convinced that fear is the dominant theme of this particular TV coverage and that much of the fear of nuclear power has elements of phobic thinking.[101]

4.3 Equity: Who Gets the Benefits and Who Takes the Risks?

The problem of equity is an age-old one that will never be resolved to everyone's satisfaction. In reality, both risks and benefits to everyone from both the nuclear and coal fuel cycles generally exist. Some are relatively immediate, others may be distributed over time and among future generations.

As discussed in Sections 2 and 3, both the nuclear and coal fuel cycles have immediate risks to populations now living. These risks include those to workers from all aspects of the fuel cycles. Because both fuel cycles tend to be distributed over large geographical areas, the public and occupational risks also are distributed over large geographical areas. As a result, while workers directly benefit from their labors (and voluntarily accept the risks in return), the people who, for example, must dodge coal trains at railroad crossings between the coal mine and the power generating station may accrue no direct benefit for their added risk of death and injury.

The same statement can be made for public risks from coal-cleaning waste and coal ash because these wastes accumulate primarily at the point where the benefits (for example, wages, taxes, and electrical power) accrue. On the other hand, the potential impacts associated with introduction of toxic trace metals into drinking water and food pathways and the ecological and materials damage from acid rain and acid mine drainage may be "exported" to people in other areas and future times who receive little or no obvious direct benefits.* This is also true for Rn-222 releases from uranium mine and mill tailings.

Economists would discount the effects on future populations by applying the principles used in determining the present worth of future dollars. Thus, if society were concerned about possible future health effects resulting from present-day technology, economists would discount these future effects at a reasonable discount rate. As an example, if one additional death resulting from the nuclear fuel cycle per reference reactor year were to occur 1,000 years from the year 0.8 Gw-yr of electric power was produced, they might discount the value of a future death by 5% per year:**

$$\begin{aligned}\text{Present value} &= V(1 + i)^{-n} = (1 \text{ future death})\,(1 + 0.05)^{-1000} \\ &= 6.5 \times 10^{-22} \text{ deaths today} \sim 0\end{aligned}$$

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*Although more uncertain, considerable indirect benefits to future generations may come from greater political, social, and economic stability resulting from a continuation of economic growth, high standards of living, and other factors that, in turn, depend on an abundance of reliable power.

**Although the absolute values used for the interest or discount rates are highly uncertain, it must be stressed that the same conclusions can be reached at higher or lower rates. Higher rates, for example, mean that less money would be set aside or, for discounting purposes, that the present worth of future deaths (or dollars) is lower than for a lower discount rate.

Clearly, this method indicates that potential health effects in the far-distant future cannot affect such things as cost/benefit balances in today's society.

4.4 Acceptable Risks Versus Accepted Risks

Fischhoff and coworkers[99] define acceptable risk as that level of risk associated with the most acceptable alternative in a decision problem. The choice of an alternative, and its accompanying risks, depends on the alternatives, consequences, facts, and values that were considered during the decisionmaking process. Many of these parameters (particularly values) tend to be volatile, and can change as new data and technological advances develop, leading to a change in the acceptability of any of the alternatives. Furthermore, it was concluded, "Even in the same situation and at a single time, different people with different values, beliefs, objectives, or decision methods might disagree on which alternative is best. In short, the search for absolute acceptability is misguided."[99]

The Commission of the European Communities (CEC) defines an acceptable risk as one "worthy of being accepted," presumably in comparison to other risks and alternatives.[100] This Commission points out that in any society risks are already present at the time decisionmaking begins. These de facto risks may be accepted or unaccepted, and merely exist. An unacceptable risk may achieve de facto status if it has no technological or economically acceptable alternatives at the time. Where these risks may be modified by technical, management, or legislative means, de facto risks may become "acceptable." In the special case of natural phenomena (acts of God), low-probability de facto risks become accepted fatalistically because there may be no reasonable alternatives to consider.

CEC also noted that in the past, the public has accepted certain risks (for example, automobile use) as familiarity with the risk has grown, even though risk experts have found the risks to be unacceptable. Thus, they argue, given adequate time and the opportunity to demonstrate its safety and economics, nuclear power could also become an "accepted" risk to a wider segment of the public.

The CEC report concluded that the status of certain risks can be categorized as shown in Table 18.

Because of the wide range of objective risks for each status category, the authors of the CEC report concluded that no correlation currently exists between acceptability or acceptance of a risk and the actual magnitude of risk. Paradoxically, they found the objective nuclear power risks are approximately 100 times below the range of 10^{-4} to 10^{-6} shown for many present-day acceptable risks. The authors were unable to clearly identify any specific factor or factors that could explain this phenomenon.

4.5 Moral and Ethical Considerations

Bioethicist Margaret Maxey has studied the ethical and moral issues associated with inequities in risk, both in space and in time. She concludes that, from the perspective of public ethics, perceived future risks from nuclear technology (for example, radioactive wastes from the nuclear fuel cycle) derive from

Table 18. Classification of risk by current status[100]

Risk	Order of Risk (deaths per person-year)
De Facto	
Natural background radiation	$\sim 10^{-5}$ (one chance in 100,000)
Floods, tornadoes, or earthquakes	$\sim 10^{-6}$ (one chance in 1 million)
Lightning	$\sim 10^{-7}$ (one chance in 10 million)
Meteorite impacts	$\sim 10^{-11}$ (one chance in 100 billion)
Acceptable and Accepted	
Occupational deaths on railways (U.K.)	$\sim 10^{-4}$ (one chance in 10,000)
Death from cholera or whooping cough	$\sim 10^{-6}$ (one chance in 1 million)
Train-passenger deaths (total)	$\sim 10^{-6}$ (one chance in 1 million)
Radiation death from consumer products	$\sim 10^{-7}$ (one chance in 10 million)
Steam-boiler explosions or dam failures (U.K.)	$\sim 10^{-7}$ (one chance in 10 million)
Radiation from high-altitude flight	$\sim 10^{-8}$ (one chance in 100 million)
Radiation from color-televison viewing	$\sim 10^{-9}$ (one chance in 1 billion)
Unacceptable and Accepted	
Risk to individuals from dam failures	$\sim 10^{-2}$ (one chance in 100)
Lung cancer risk from smoking (20 cigarettes/day) or therapeutic use of antibiotics	$\sim 10^{-3}$ (one chance in 1,000)
Therapeutic use of antidepressant or antihypertensive drugs	$\sim 10^{-4}$ (one chance in 10,000)
Overall road-accident deaths	$\sim 10^{-4}$ (one chance in 10,000)
Death from use of contraceptive pills or tuberculosis*	$\sim 10^{-5}$ (one chance in 100,000)
Public risk from fossil fuel combustion* or therapeutic use of antirheumatic drugs or death from diagnostic radiology	$\sim 10^{-6}$ (one chance in 1 million)
Acceptable and Not Accepted	
Brain damage from whooping cough vaccination	$\sim 10^{-4}$ (one chance in 10,000)
Passenger deaths in aircraft accidents	$\sim 10^{-5}$ (one chance in 100,000)
Dike flooding (Holland)	$\sim 10^{-7}$ (one chance in 10 million)
Average radiation risk to U.S. population from nuclear power**	$\sim 10^{-9}$ (one chance in 1 billion)
Unacceptable and Not Accepted	
Death from all causes at age 55	$\sim 10^{-3}$ (one chance in 1,000)
Occupational pneumoconiosis	$\sim 10^{-3}$ (one chance in 1,000)
Death from cancer, stroke, or heart disease	$\sim 10^{-3}$ (one chance in 1,000)
Death from bronchitis or influenza	$\sim 10^{-4}$ (one chance in 10,000)
Occupational death in chemical industry	$\sim 10^{-4}$ (one chance in 10,000)
Death from leukemia or tuberculosis*	$\sim 10^{-5}$ (one chance in 100,000)
Public risk from fossil fuel combustion*	$\sim 10^{-6}$ (one chance in 1 million)

*Borderline cases; could be either "Unacceptable and Accepted" or "Unacceptable and Not Accepted."

**Predicted figure. No statistics available.

"public misperceptions of the risks involved and the ease with which those misperceptions have been exploited for ulterior political purposes by those who have chosen to politicize the nuclear energy option of this nation."[102]

Furthermore, she argues that the use of irreplaceable hydrocarbons for generating energy when other fuels are available may be immoral because it deprives future generations of basic goods:

> Public policy should exercise wise stewardship...by giving priority development to energy-only resources--i.e., uranium, thorium, deuterium--so as to preserve for future generations the basic goods derived from precious hydrocarbons (medicines, fertilizers and pesticides for increased food production, petrochemicals, etc.) which have no known or feasible substitutes.[103]

Maxey concludes that the problems being encountered by the nuclear power industry are only symptoms of a much deeper problem. She concludes, "The public must be educated to reallocate the financial and social costs of safety. Zero risks and absolute safety are indeed costly illusions. Man does not live by safety alone. The ultimate challenge is to rediscover what else we live by."[102]

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5 SUMMARY AND CONCLUSIONS

All the items considered in this report lead to the inevitable conclusion that, although the health risks of both the nuclear or coal fuel cycles are very small in relation to other everyday sources of risk, the coal fuel cycle certainly results in a much greater impact on man and his environment than does the nuclear fuel cycle. This conclusion stands even when the uncertainties in these estimates are included, as long as one compares the lower- and upper-bound estimates of the fuel cycles or the most realistic estimates of risk for both fuel cycles.

As shown in Sections 2 and 3, even if the risks from toxic and radioactive materials are much higher (factors of 10 to 100) than is currently believed, the risks of mortality and injury to the general public would not be great in relation to the most common causes of death and injury in the United States.

Finally, an examination of several of the subjective aspects of risk assessment leads to the conclusion that although these factors are operating in human society, there are no immediate prospects for their inclusion in quantitative risk assessment.

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7 GLOSSARY

BEIR	biological effects of ionizing radiation
Btu	British thermal unit
CEC	Commission of the European Communities
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
CONAES	Committee on Nuclear and Alternative Energy Systems, NAS
CWP	coal workers' pneumoconiosis
EDC	environmental dose commitment
EPA	Environmental Protection Agency
FGD	flue gas desulfurization
GESMO	Generic Environmental Impact Statement on Use of Mixed Oxide Fuel
ICRP	International Commission on Radiological Protection
LET	linear energy transfer
LWR	light-water reactor
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NRC	Nuclear Regulatory Commission
PMF	progressive massive fibrosis
ppm	parts per million
RRY	reference reactor year
U.K.	United Kingdom
WLM	working-level months

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Estimates of mortality and morbidity are presented based on present-day knowledge of health effects resulting from current component designs and operations of the nuclear and coal fuel cycles, and anticipated emission rates and occupational exposure for the various fuel cycle facilities expected to go into operation during the next decade. The author concluded that, although there are large uncertainties in the estimates of potential health effects, the coal fuel cycle alternative has a greater health impact on man than the uranium fuel cycle. However, the increased risk of health effects for either fuel cycle represents a very small incremental risk to the average individual in the public for the balance of this century. The potential for large impacts exists in both fuel cycles, but the potential impacts associated with a runaway Greenhouse Effect from combustion of fossil fuels, such as coal, cannot yet be reasonably quantified. Some of the potential environmental impacts of the coal fuel cycle cannot currently be realistically estimated, but those that can appear greater than those from the nuclear fuel cycle.

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